SUMMARY TECHNICAL REPORT
OF THE
NATIONAL DEFENSE RESEARCH COMMITTEE

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SUMMARY TECHNICAL REPORT OF DIVISION 16, NDRC

VOLUME 1

OPTICAL INSTRUMENTS

OFFICE OF SCIENTIFIC RESEARCH AND DEVELOPMENT

VANNEVAR BUSH, DIRECTOR

NATIONAL DEFENSE RESEARCH COMMITTEE

JAMES B. CONANT, CHAIRMAN

DIVISION 16

GEORGE R. HARRISON, CHIEF

WASHINGTON, D. C., 1946

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NOTES ON THE ORGANIZATION OF NDRC

The duties of the National Defense Research Committee were (1) to recommend to the Director of OSRD suitable projects and research programs on the instrumentalities of warfare, together with contract facilities for carrying out these projects and programs, and (2) to administer the technical and scientific work of the contracts. More specifically, NDRC functioned by initiating research projects on requests from the Army or the Navy, or on requests from an allied government transmitted through the Liaison Office of OSRD, or on its own considered initiative as a result of the experience of its members. Proposals prepared by the Division, Panel, or Committee for research contracts for performance of the work involved in such projects were first reviewed by NDRC, and if approved, recommended to the Director of OSRD. Upon approval of a proposal by the Director, a contract permitting maximum flexibility of scientific effort was arranged. The business aspects of the contract, including such matters as materials, clearances, vouchers, patents, priorities, legal matters, and administration of patent matters were handled by the Executive Secretary of OSRD.

Originally NDRC administered its work through five divisions, each headed by one of the NDRC members. These were:

Division A—Armor and Ordnance
Division B—Bombs, Fuels, Gases, & Chemical Problems
Division C—Communication and Transportation
Division D—Detection, Controls, and Instruments
Division E—Patents and Inventions

In a reorganization in the fall of 1942, twenty-three administrative divisions, panels, or committees were created, each with a chief selected on the basis of his outstanding work in the particular field. The NDRC members then became a reviewing and advisory group to the Director of OSRD. The final organization was as follows:

Division 1—Ballistic Research
Division 2—Effects of Impact and Explosion
Division 3—Rocket Ordnance
Division 4—Ordnance Accessories
Division 5—New Missiles
Division 6—Sub-Surface Warfare
Division 7—Fire Control
Division 8—Explosives
Division 9—Chemistry
Division 10—Absorbents and Aerosols
Division 11—Chemical Engineering
Division 12—Transportation
Division 13—Electrical Communication
Division 14—Radar
Division 15—Radio Coordination
Division 16—Optics and Camouflage
Division 17—Physics
Division 18—War Metallurgy
Division 19—Miscellaneous
Applied Mathematics Panel
Applied Psychology Panel
Committee on Propagation
Tropical Deterioration Administrative Committee

[redacted]

NDRC FOREWORD

As EVENTS of the years preceding 1940 revealed more and more clearly the seriousness of the world situation, many scientists in this country came to realize the need of organizing scientific research for service in a national emergency. Recommendations which they made to the White House were given careful and sympathetic attention, and as a result the National Defense Research Committee [NDRC] was formed by Executive Order of the President in the summer of 1940. The members of NDRC, appointed by the President, were instructed to supplement the work of the Army and the Navy in the development of the instrumentalities of war. A year later, upon the establishment of the Office of Scientific Research and Development [OSRD], NDRC became one of its units.

The Summary Technical Report of NDRC is a conscientious effort on the part of NDRC to summarize and evaluate its work and to present it in a useful and permanent form. It comprises some seventy volumes broken into groups corresponding to the NDRC Divisions, Panels, and Committees.

The Summary Technical Report of each Division, Panel, or Committee is an integral survey of the work of that group. The first volume of each group's report contains a summary of the report, stating the problems presented and the philosophy of attacking them, and summarizing the results of the research, development, and training activities undertaken. Some volumes may be "state of the art" treatises covering subjects to which various research groups have contributed information. Others may contain descriptions of devices developed in the laboratories. A master index of all these divisional, panel, and committee reports which together constitute the Summary Technical report of NDRC is contained in a separate volume, which also includes the index of a microfilm record of pertinent technical laboratory reports and reference material.

Some of the NDRC-sponsored researches which had been declassified by the end of 1945 were of sufficient popular interest that it was found desirable to report them in the form of monographs, such as the series on radar by Division 14 and the monograph on sampling inspection by the Applied Mathematics Panel. Since the material treated in them is not duplicated in the Summary Technical Report of NDRC, the monographs are an important part of the story of these aspects of NDRC research.

In contrast to the information on radar, which is of widespread interest and much of which is released to the public, the research on subsurface warfare is largely classified and is of general interest to a more restricted group. As a consequence, the report of Division 6 is found almost entirely in its Summary Technical Report, which runs to over twenty volumes. The extent of the work of a division cannot therefore be judged solely by the number of volumes devoted to it in the Summary Technical Report of NDRC: account must be taken of the monographs and available reports published elsewhere.

Division 16 carried out a broad program in the fields of light and optics. Among the studies undertaken were a number involving the principles and techniques of camouflage, and perhaps the outstanding success achieved in this field was the development of the "black widow" finish for night-flying aircraft. Significant improvements were made in aerial mapping and photography. Devices depending on the use of infrared light were developed for the detection of enemy craft, the recognition of friendly ones and for intercommunication by voice and code. The sniperscope, using image-forming infrared rays, was a spectacular weapon which enabled our troops to fire accurately on an enemy 100 yards away in utter darkness.

The Division 16 Summary Technical Report, prepared under the direction of the Division Chief, George R. Harrison, describes the technical achievements of the Division personnel and its contractors, and is a record of their skill, integrity, and loyal cooperation. To all of them, we extend our grateful praise.

VANNEVAR BUSH, Director
Office of Scientific Research and Development

J. B. CONANT, Chairman
National Defense Research Committee

PREFACE

SECTION 16.1, Optical Instruments, of NDRC was organized in December 1942 to continue the work on optical instruments for which Section D-3, Instruments, had been responsible, along with many other types of physical equipment, from July 1940 to December 1942. The work of Section 16.1 continued until June 28, 1946.

The membership of Section 16.1 was drawn from universities and research institutions. Ira S. Bowen, Professor of Physics at the California Institute of Technology, and after January 1, 1946, Director of the Mount Wilson Observatory, contributed his wide knowledge of physical optics and instrument design, particularly in the field of aerial photography. William V. Houston, Professor of Physics at the California Institute of Technology, who was recently appointed President of the Rice Institute, brought his extensive experience in physics to bear on many problems, particularly those relating to aerial photography and binocular performance. Robert R. McMath, Director of the McMath-Hulbert Observatory and Professor of Astronomy at the University of Michigan applied his unusual experience in optical engineering to many of the projects, particularly aerial photography, stabilized mounts and phototheodolites. Frederick E. Wright, of the Geophysical Laboratory of the Carnegie Institution of Washington, who was Technical Adviser to the Joint Optics Committee of the Army-Navy Munitions Board during World War II and who was responsible for matters relating to the production of optical instruments during the first world war contributed many of the ideas which guided decisions regarding ordnance projects, particularly those relating to optical inspection and tropical deterioration. George W. Morey, who is also a member of the Geophysical Laboratory, applied his knowledge of methods of growing and testing crystals to the project aimed at developing artificial fluorite. All of these men took an active part in planning and supervising individual projects. The aim was to obtain basic data by quick intensive studies whenever necessary, while pushing ahead developments for Service applications as rapidly as possible. Theodore Dunham, Jr., of the Mount Wilson Observatory of the Carnegie Institution of Washington, served as chief of the Optical Instruments Section and devoted full time to studying Army and Navy requirements, implementing decisions reached at meetings of the Section, visiting contractors' laboratories, operating the Section Office and, after the end of the war, editing this volume.

Harold F. Weaver of the Yerkes Observatory, Sidney W. McCuskey of the Case School of Applied Science, and Lillian R. Elveback of the University of Minnesota, served as Technical Aides to Section 16.1 for various periods of time. Dr. Weaver and Miss Elveback were largely responsible for supervising the binocular programs, whereas Dr. McCuskey spent much time on the optical plastics program. The success of the Section was largely due to the imagination and effort of the Technical Aides.

Herman F. Mark, who is well known for his work on high polymers, served as consultant on the project for developing optical plastics. He made many stimulating suggestions regarding the program and regarding the report on this subject. Dr. Morey served as consultant on artificial fluorite and on optical plastics before his appointment as a member of the Section. Harold F. Weaver served as consultant on the project relating to binocular performance.

No account of the activities of the Section would be complete without referring to the strikingly efficient work and splendid spirit of the secretarial staff, headed by Margaret M. Connolly. Without this unusual group of young women, who throughout the war did far more than was expected of them, the results would have been much less effective.

A large part of the program has been carried out in close contact with the Services. The work on aerial photography required close cooperation with the Photographic Laboratory at Wright Field and the use of Army aircraft for the testing program at Bedford. The work on optical inspection required even closer cooperation with the Frankford Arsenal, where many officers supplied basic ideas. The Office of the Coordinator of Research and Development (later known as the Office of Research and Inventions), the Hydrographic Office and the Bureau of Aeronautics in the Navy provided valuable information on mapping requirements and methods. The Section is particularly indebted to H. Noble of WDLO and to H. G. Dyke of the Coordinator's Office for the imagination

and assistance which they gave in the solution of a vast number of problems involving liaison which arose in connection with the projects. Differences of opinion with the Services frequently developed, both regarding the planning of projects and regarding the testing of procedures and equipment, but in almost every case these were resolved without difficulty.

The contractors and individual workers in the various laboratories deserve the greatest credit for the success of the projects on which they worked. Without exception they dropped other scientific and commercial undertakings not related to the war effort, and concentrated all of their resources on achieving solutions to NDRC problems. The experience of all divisions of NDRC shows that successful results can be achieved quickly by balanced teams of scientists and engineers working in accordance with a carefully formulated plan, toward a common objective. The extent to which similar joint efforts are indicated, and can be carried out in peacetime without stifling individual initiative may be usefully considered on the basis of the detailed history of NDRC projects.

The present volume represents an attempt to give in condensed form a technical report on the activities of Section 16.1. Almost every project, even those of apparent minor importance has been at least briefly described. Experience has shown that projects which seemed relatively unimportant while work was in progress often assumed unexpected importance later in planning other projects. Full references are given to OSRD reports in which the original work is described. Microfilms of all of these reports are available. It is unfortunate that time has not been adequate for discussing fully many of the projects described in this report. The aim has been to present at least representative samples of all results, so that the reader may draw his own conclusions regarding the significance of the work.

The contractors' reports have served as the basis for the text of this volume. In general they have been summarized in approximately 30 per cent of the original number of words. Frequently parts of the original text have been used unchanged. In such cases, quotation marks ordinarily have not been used in order to simplify the final text as much as possible. In all cases, however, references are given to the original sources.

Recommendations for further work on those projects where more remains to be done have been given careful consideration by the Section. They are grouped together at the ends of the chapters to which they apply under the heading "Recommendations by NDRC." The Section, not individual writers, is responsible for these recommendations, although they have been discussed with the writers, who have themselves suggested many of the recommendations.

The following individuals have compiled chapters or parts of chapters in this volume: James G. Baker, Harvard College Observatory; J. S. Chandler, Eastman Kodak Co.; Theodore Dunham, Jr., Chief, Section 16.1 (also editor), NDRC; John W. Evans, University of Rochester; Howard S. Coleman, Pennsylvania State College; Hobert W. French, Argus, Inc.; Leo Goldberg, McMath-Hulbert Observatory; H. K. Hartline, Johnson Foundation, University of Pennsylvania; Duncan MacDonald, Physics Department, Boston University; Sidney W. McCuskey, Case School of Applied Science, Warner and Swasey Observatory; Robert R. Singleton, Merrill Flood and Associates.

The splendid cooperation of those who have prepared material for this volume in the limited time available is very much appreciated.

THEODORE DUNHAM, JR.
Chief, Section 16.1

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SUMMARY

By *Theodore Dunham, Jr.*[a]

THE WORK OF Section 16.1 was extremely varied. It included (1) basic studies, such as binocular performance tests at low levels of illumination, the investigation of factors limiting resolution in aerial photography, and the development of methods for preventing tropical deterioration in optical instruments, (2) studies of existing methods, followed by the development of improved methods, such as the work on mapping and optical inspection, (3) the development of new laboratory techniques, such as those for growing large artificial fluorite crystals, for high efficiency coating, milling and figuring of roof prisms, glass molding, and casting of optical plastic elements, (4) the development of special procedures, such as those for harmonizing B-29 guns and sights in the field, and (5) the development of a wide variety of optical and mechanical devices to meet specific military needs, such as precision aerial camera lenses and mounts, special telescopes, wide-field binoculars, improved periscopes and projecting systems, reflex sights, stadiameters, antioscillation mounts for optical instruments, phototheodolites, optical scanning devices, an antiglare shutter for night binoculars, rapid processing equipment for periscope photography, and a two-star navigating device for use in aircraft.

The work was done under eighteen contracts with research institutions and under twelve contracts with industrial laboratories. The development of methods for preventing tropical deterioration in optical instruments was transferred to the Tropical Deterioration Administrative Committee in 1945.[b]

Particular attention was devoted to aerial photography which provides in wartime a large part of all available information about enemy territory, the disposition of men, equipment and shipping, and the damage inflicted as the result of raids, all of which serves to guide future military operations. The usefulness of an aerial photograph depends largely on the detail which it records, and ordinarily the ability of an interpreter to distinguish and identify objects on the ground increases very rapidly with improving quality of the photograph.

The work on aerial photography was carried out under Project AC-29 which covered the development of a number of special cameras, lenses, and shutters, and under Project AC-88 which covered studies of the factors which limit resolution. The aim was to increase the linear scale of the photographs by using lenses of longer focal length than had previously been employed, and at the same time to improve the resolution as much as possible. Photographs of high quality can be made only with a lens of high intrinsic resolution, accurate location of the film in the focal plane, freedom from angular vibration and from differential linear vibration of the camera and lens elements, and sufficient aperture to permit optimum exposure with an emulsion having good resolution.

Several lenses of unusually high performance were designed and constructed at Harvard University. The most significant of these was, undoubtedly, the 40-in. $f/5$ lens with automatic control of focus and temperature. This lens was procured by the Army Air Forces [AAF] and some units were used overseas. The performance was markedly superior to that of standard lenses previously used and demonstrated convincingly the striking improvement that can be achieved when every effort is made not only to design the lens to concentrate all the rays of light from a distant point in the smallest possible region at the focus, but also to design a mount which will hold the lens elements accurately in position without strain. Several other high-performance lenses were developed, including a color-free glass-fluorite 36-in. $f/8$ lens, a 36-in. $f/8$ 9x18 lens, and a 100-in. $f/10$ lens. At the end of World War II, a 60-in. $f/5$ 9x18 lens, which incorporated all of the new experience with optical and mechanical designs, was under construction. This lens was to be

[a] Chief, Section 16.1, NDRC (Mount Wilson Observatory).

[b] These methods are described in Summary Technical Report of the Tropical Deterioration Administrative Committee.

sealed at the front and back with plates of optical glass, and the system was to be evacuated to eliminate changes of focus due to variation in barometric pressure and to prevent condensation of moisture and tropical deterioration. It would be very desirable to finish this lens and to test it thoroughly.

Extensive programs covering tests of the laboratory performance of lenses have been carried out at the Eastman Kodak Company and the Mount Wilson Observatory. The results are important, not only for guidance in the selection of lenses for special application by the Services, but for providing the lens designer with information regarding the overall lens-film performance that is given by various designs.

Considerable attention has been given to the development of Schmidt cameras (Mount Wilson, the Massachusetts Institute of Technology [MIT] and Harvard) primarily to provide fast systems for night flash photography. A particularly promising Schmidt camera developed at Harvard operates at $f/1.3$ and uses continuously running motion-picture film with intermittent Edgerton flashes to produce a series of exposures which can later be fitted together to make a long strip photograph. An $f/1.0$ lens was developed by the University of Rochester which covers 40 degrees with good definition. The field is strongly curved, but air pressure is used to make the film conform to the required surface.

Improved camera mounts have been developed (Eastman and Mount Wilson) to reduce as far as possible the transmission of vibration from the fuselage to the camera and to compensate image motion due to forward motion of the aircraft. Experiments have also been carried out with gyrostabilized mounts to eliminate the effects of long-period roll and pitch.

Several developments on camera shutters were carried out by Mount Wilson, Eastman, and Technicolor Motion Picture Corporation. The speed of the between-the-lens shutter of the 6-in. Metrogon camera was considerably increased by reducing the inertia of the driving cam, and by mounting its shaft on ball bearings. Some improvement in the speed of the 24-in. between-the-lens shutter was also achieved, but not enough to warrant changes in production. A two-blind multiple-slit Langer shutter was developed at Mount Wilson and at Technicolor in an attempt to increase speed, make all parts of a photograph represent more nearly simultaneous exposures, and increase life of the ordinary focal plane shutter. These efforts were only partially successful. The shutter problem is a difficult one, but it deserves a concentrated attack. A more efficient and a faster shutter is one of the most immediate means for achieving better resolution on aerial photographs, without waiting to improve mounts.

Unfortunately the resolution of high-quality lenses, when used under standard flight conditions, appears to be only slightly more than half as much as the resolution which the same lenses are capable of giving under laboratory conditions. This means that much information of great potential value is being missed on photographs, and can only be regained at present by nearly doubling the focal length of the camera. An extensive investigation of this situation was carried out at Harvard, Eastman, and Mount Wilson. Laboratory studies were supplemented by flight tests at Bedford, Mass., including the recording of camera vibrations under operating conditions. The results show clearly that forward motion of the aircraft is the most serious factor that limits resolution, but that roll and pitch of the fuselage, vibration transmitted to the cameras through their mounts, and vibration caused by shutter recoil and low optical quality of standard photographic windows combine to reduce to a marked extent the detail which can be detected on photographs. Each of these factors can unquestionably be reduced to an unimportant level by suitable engineering of the accessory equipment. The resolving power (altitude of aircraft divided by spacing of high-contrast black and white lines resolved on the ground) of the standard 24-in. camera under average operating conditions probably rarely exceeds 8,000. A suitable mount and better windows would probably increase this value at least to 12,000. The 40-in. Harvard-NDRC lens in an improved mount has given an average resolving power of 30,000, and this can undoubtedly be increased still further. The 60-in. and 100-in. lenses, properly mounted, should have resolv-

ing powers of at least 45,000 and 70,000, respectively.

It must be emphasized that, while it is easy to produce photographic equipment with a resolving power of 10,000, this is about the limit that can be attained without special effort. Higher resolving powers require larger and much heavier cameras with special mounts and temperature control. The production and operation of such equipment in aircraft appears, however, to be entirely practical, and the tremendous importance of the information which would be gained by using such equipment for reconnaissance fully justifies the effort involved in the undertaking.

It cannot be expected that personnel with average training can operate special equipment to full advantage. A group should therefore be trained in the operating and servicing of precision photographic equipment. Special squadrons of aircraft with precision equipment of the latest type should be reserved for exclusive use by this group over special targets. This group should report directly to a high level in the AAF, and should be in direct touch with all laboratories where development work is in progress. In response to special requests, such a group could unquestionably provide military information of great importance.

Improved mounts for gun cameras were developed by the Eastman Kodak Company under Project AC-99. Tests with high-speed cameras and mirrors attached to various parts of the Martin upper turret indicated that angular vibration is extreme, even in the gun receiver, and that improvements in the linkage to the sight would do little to improve the present low quality of photographs. A gimbal mount was developed and tested by the Navy at Patuxent with encouraging results. An antioscillation mirror mount for the Gun Sight Aiming Point camera [GSAP] on the K-15 sight was developed. The logical solution would be to incorporate the camera in the sight. Much could be done to produce sharper individual photographs by merely shortening the exposure time. Under most operating conditions the $f/3.5$ lens would permit reducing the exposure by a factor of several times, which could be accomplished by reducing the sector opening of the shutter.

A method for mapping from high oblique photographs was developed by Merrill Flood and Associates under Project NA-124. A survey of the requirements of the Navy and of available methods in Washington and at Pearl Harbor showed that mapping from vertical photographs could be carried out effectively with multiplex equipment, but that in many cases it would be advantageous to be able to use oblique photographs, either because of difficulties encountered in making verticals due to clouds or enemy interference, because of the reduction in the required amount of flying when obliques are used, or because of the advantages which obliques offer for certain purposes, such as relating islands which are widely separated by water and covering wide areas of land in single photographs.

A pinhole photographic rectifier was developed by the Aero Service Corporation, and was taken to Pearl Harbor for testing. A simple lens designed at Harvard greatly improved the resolution. This was followed by a Hypergon lens which gave still better results.

The method of mapping developed by Merrill Flood and Associates is based on the use of a fixed-angle rectifying camera with a Hypergon lens, designed for photographs of 60 degrees tilt. Variations in this tilt are compensated by a preliminary reduction of the scale of the original negative by the appropriate ratio to adapt the perspective index to the rectifying camera. This procedure permits great simplification of equipment. Following rectification, the photograph is enlarged or reduced to the desired scale. A precision variable-ratio printer was developed by the Aero Service Corporation and a fixed-angle rectifying camera was designed and built by Merrill Flood and Associates. An orthographic plotter was also developed for drawing contours from the photographs. Tests of the method show that it is entirely practical and that it gives the desired accuracy. Production tests will be required to evaluate the effectiveness and cost of the method in comparison with other methods.

The determination of depth of shallow water is a matter of great importance in the planning of amphibious assault operations. Many methods have been proposed. One of the most prom-

ising of these is based on the use of the Sonné stereostrip camera at altitudes of less than 500 ft, and was developed by the Photographic Interpretation Center. An alternative method was proposed by Merrill Flood and Associates, based on the use of two standard strip cameras mounted in the wings of an airplane, so that the base line and relative orientation are known. This method seems promising, provided that the flexure of the inner parts of the wings where the cameras would be mounted, is not too great. A test installation was under way at the Naval Aircraft Factory at the end of World War II.

It is desirable that the Army and Navy maintain mapping organizations with well-trained personnel at all times, and that other Government and civilian agencies be asked to cooperate in a program aimed at mapping wide areas of territory and developing improved methods and equipment. The Navy should maintain mobile fully equipped units for mapping special distant regions. Pilots and other personnel should be trained especially for mapping, as distinguished from reconnaissance. A well-planned program for further development of mapping methods should be undertaken with Government funds, so that this country will be in a strong position regarding the application of photogrammetric techniques if another emergency should arise.

A study of optical inspection methods used to control production was made by the Pennsylvania State College under Project OD-138. A report was made on the methods which were in use in 1945 at various Government and commercial production plants. A program was also undertaken aimed at developing methods of inspection which would eliminate, as far as possible, the variable factor of human judgment.

The staff of the Frankford Arsenal gave much valuable advice and assistance throughout the programs. An impersonal method for measuring the overall resolution of a telescope system was developed. The equipment, known as the *Kinetic Definition Chart* [KDC] apparatus provides images of a parallel-line test object in which the apparent angular spacing can be varied continuously by changing the distance between the object itself and a microscope objective. The observer compares the minimum resolvable angular spacing for the telescope under test with that for a telescope of nearly perfect optical quality, thus establishing the resolution of the instrument on a percentage basis. The KDC apparatus was adopted by the Ordnance Department and was used to control the production of a large number of tank telescopes and of some other optical instruments. The accuracy and consistency of measures made with the equipment were studied extensively at Penn State. Further investigations are needed to determine the most effective value for the auxiliary magnification which is ordinarily employed with the KDC apparatus.

Several additional laboratory studies and developments were made. The usefulness of the interferometer for inspecting individual optical elements and subassemblies was established and an improved design for an inspection interferometer was developed. An improved dioptometer was also developed and applied to a number of inspection problems.

The resolving power of the eye with Foucault test patterns was measured, using stops of VARI-ous diameters. The observed values exCEEDED those indicated by the Rayleigh criteriON FOR optical instruments when the diameter OF THE pupil was less than 1 mm. This result is, HOWever, explained to a large extent by the fact that a Foucault pattern with ten parallel black lines was used, whereas the Rayleigh criterion is based on the use of only two lines. Experiments showed that when two lines are used the resolving power of the eye is reduced by about 30 per cent, which makes it slightly less than that indicated by the Rayleigh criterion.

Equipment was devised for measuring the amount of light scattered into the image and the resulting reduction of contrast in telescope systems. The performance of a telescope in this respect may be as important as its resolving power at low levels of illumination. It is desirable that a comparison be made of scattered light in coated and uncoated telescope systems, since there are indications that in some cases coating increases the amount of light scattered.

In order to establish the physical perform ance of telescope systems on a strictly imp sonal basis, measures have been made of th

tensity distribution of light in the image of a distant line source, using a modification of the photographic wedge method developed by Jones and Wolfe, and also using a traveling slit and photoelectric recorder. Both methods give data which are of fundamental importance, not only for evaluating various methods of optical inspection, but also for establishing the performance of new optical designs. It would be desirable to have measures of light distribution made in images formed by a number of representative fire-control instruments, on and off axis, and at various focal settings, to provide a basis for comparing different methods of inspection.

Studies of binocular performance were carried out, under Project NO-210, at the Dartmouth Eye Institute, at Brown University, and at the University of Pennsylvania, to determine the optimum design characteristics of hand-held binoculars intended for use in detecting targets by night lookouts on ships. The effects of varying magnification and exit pupil diameter separately and simultaneously were investi-...d by observing the ranges at which small targets could be detected at low levels of ...nation under laboratory conditions. Time ...not permit a study of the effects of these ...tors on target recognition or a study of the effect of the diameter of the field of view on detection.

It is well known that an increase in the magnification of a binocular leads to an increase in the range at which objects can be detected at night, and that this is usually the most important single factor in the design of a binocular which controls the range of detection. There is, however, a limit to the magnification that can be used in practice, since if the diameter of the exit pupil is held constant, the size, weight, and cost of the instrument increase rapidly because of the need for increasing the diameter of the objectives in the same proportion as the magnification. The results at Dartmouth and at Brown show that an increase in the diameter of the exit pupil leads to a rapid increase in the range of detection up to 6 mm, with a much slower increase up to about 8 mm, after which there is no further gain. Maximum range of de-...ion with 50-mm objectives is attained at 10× magnification in the laboratory, but the gain as compared with the standard 7x50 binocular amounts to only about 10 per cent. The failure of higher magnifications to give increased ranges is only partly due to the reduced exit pupil. The inevitable reduction in eye relief and the more restricted field of view are also important factors. The results of the binocular testing program show that it is not possible to achieve any striking gain in range by changing the magnification or exit pupil of a hand-held binocular, which must be kept within reasonable dimensions. It is nevertheless possible that moderate gains may be important from a military point of view, since the purpose of a lookout is to detect the enemy before being himself detected. Under these conditions, even a small advantage may be decisive.

The gain in the range at which targets can be detected with binoculars at night would, theoretically, be expected to equal numerically the value of the magnification, provided the exit pupil is larger than the pupil of the eye, and provided there is no loss of light in the optical system of the binocular. However, the results at Brown show that the gain in range is usually only a little more than half the value to be expected from the magnification after light losses are taken into account.

In an attempt to uncover the reason for this failure of the gain in range due to binoculars to measure up to expectations, several experiments were carried out at Brown. It was found that alidade mounting of the binoculars increased range about 8 per cent, as compared with hand-held instruments. Headrests for the binoculars, which might be expected to aid in holding the exit pupil in line with the pupil of the eye, made little difference under laboratory conditions. Rolling the observer in a Scoresby machine with an amplitude of 14 degrees and a period of 9 sec to simulate motion on shipboard reduced range by 15 per cent. A comparison between monocular and binocular vision showed that binocular vision increases range by 15 per cent with the instrument, as compared with slightly more than 20 per cent when the naked eyes alone are used. None of these results was adequate to explain the low gain in range due to binoculars in laboratory tests.

Experiments carried out at the University of Pennsylvania showed that the loss in expected range can be entirely explained as the result of "clipping" (lack of alignment of the exit pupil of the instrument and the pupil of the eye) and of angular tremor due to unsteadiness of holding. Binoculars fixed rigidly to the skull by means of a bite, in the correct position of alignment, gave the full gain in range that was to be expected on the basis of magnification. This suggests that eye guards in contact with the face and with the side of the head would be helpful on shipboard where wind and vibration increase the difficulty of maintaining proper alignment of binoculars and cause considerable angular motion of the image.

Infrared photographs taken through the objectives in the laboratory at the University of Pennsylvania showed the relation of the two apertures (the exit pupil of the instrument and the pupil of the eye) at the moments when exposures were made, and gave a basis for calculating the average light loss due to clipping. Direct measurements of tremor in hand-held binoculars have also been made by photographing a distant lamp with a light camera attached to the binocular. The resulting irregular path recorded by the image on the film showed that in the laboratory the tremor of large and small binoculars was much the same. The radius of the area covered by angular motion was about 1 mil, and the period of the tremor was about 1 sec, with higher frequencies superposed. Tests on shipboard showed that the amplitudes were about three times as large.

The effect of tremor is to spread the image, as the eye sees it, over an area the radius of which is equal to the mean radius of tremor of the binocular multiplied by $M - 1$, where M is the magnification. If the tremor is fast enough, the result is that the signal is spread over a considerable area of the retina, and is less effective in producing a response than if it were concentrated in one place. Data on the visibility of large targets of low contrast, as compared with smaller targets of higher contrast but with the same integrated brightness difference, indicated that the tremor disk of hand-held binoculars has a radius of about 1 mil. Since misalignment is partly responsible for the loss in range, the indicated radius of the tremor disk should probably be reduced somewhat. Moreover, the retina cannot integrate perfectly an image wandering within a limited area when the period is as long as 1 sec. Accordingly, the suggested interpretation is subject to appreciable correction when knowledge of these properties of the retina becomes more complete, but the general picture of the process involved is undoubtedly valid.

Eye guards, intended for attachment to standard binoculars, were developed at the University of Pennsylvania. Although these eye guards did not increase range of detection under laboratory conditions, it seems almost certain that they would do so if used by lookouts on shipboard, partly because of the increase in comfort and resulting general efficiency of the observer, but primarily because, in the presence of wind and vibration, eye guards are almost certain to improve the alignment of the instrument with the eye.

Experiments made with binoculars to which weighted arms had been attached to increase their moment of inertia showed a definite reduction in angular tremor and suggested that it would be worth while to test the performance of such binoculars on shipboard. If a spring were provided to relieve the observer from carrying the extra weight on his elbows, and if vibration-filtering supports (perhaps air cushions) were provided for his elbows, it seems entirely possible that the efficiency of lookouts would be noticeably increased.

Binoculars have been shown, on the basis of the tests at Brown, to be capable under laboratory conditions of increasing the range at which objects can be detected at night by a factor of about 4.5 when the optimum magnification of $10\times$ is used. On shipboard, it may be that the optimum magnification will be found to be slightly lower, but it is nevertheless likely that some gain in range would result if the magnification of the standard 7x50 were increased to $8\times$ or $9\times$, without changing the present 50-mm aperture. The effect of fatigue on the value of the optimum magnification, under normal lookout conditions, has not yet been investigated. When this effect is known, it may change the optimum magnification appreciably. No

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for color photography when long focal lengths are employed. No elements have broken due to temperature changes resulting from flights to 30,000 ft. Because of the relatively high temperature coefficient of the index of refraction of fluorite, all lenses which include fluorite elements should be thermostated to prevent change in focal setting.

An extensive program to develop methods for fabricating optical plastic elements was undertaken by the Polaroid Corporation. It was hoped that lenses and prisms of quality adequate for fire-control instruments might be made, thus relieving the requirements for optical glass and at the same time employing methods of manufacture which could use labor not possessing the special skills required for work on optical glass. It was hoped also that materials with new and desirable optical properties might become available. Finally, there was the possibility that aspherical elements could be cast economically, thus opening up new opportunities for lens design.

Following extensive experiments, a method for casting optical plastic elements, with high internal homogeneity and very fair surface accuracy, was developed. Although the surfaces of a lens 3 in. in diameter usually depart from perfect spheres by one or two fringes, and not infrequently by more, this is not much inferior to the quality of many production glass lenses, and is entirely adequate for use in many fire-control instruments. The most successful method of fabrication depends on partially polymerizing the monomer with a catalyst while stirring constantly in an inert atmosphere. When the material is thick, but can still be poured, it is introduced into polished Pyrex molds and is baked at two successive temperatures, usually not exceeding 80 C, to complete the polymerization process. The plastic elements are separated from the molds by passing them through four successive water baths, each cooler than the last. A high percentage of the lenses and prisms emerge with almost perfect surfaces, free from defects. Prisms are cast in plate-glass molds and are welded together with low fusing alloy in jigs. The surface accuracy of prisms is not as good as that of lenses, because of the nonuniform depth of the material below different parts of the surface.

More than one hundred new plastics were synthesized, in accordance with a carefully planned program which sought to produce materials having optical properties suited to the needs of lens design. The two most satisfactory materials for general use that have been encountered so far are cyclohexylmethacrylate [CHM] and styrene. These resemble, in their general optical characteristics, crown and flint glass, respectively. They are highly transparent and almost free from color. In spite of considerable improvements, styrene still exhibits enough haze to prevent its use for prisms in binocular erecting systems, because of the loss of contrast that is involved. Styrene lenses and prisms can be cast with greater surface accuracy than CHM elements.

The surfaces of all the linear polymers that have been studied are relatively soft and must be protected from scratching by glass cover plates if they are to be used in the field. A process for hardening the surface by exposing the material to silicon tetrachloride vapor followed by hydrolysis was developed at the California Institute of Technology. This treatment increased the length of time required to produce a certain level of scratching by a factor of more than ten. Promising experiments on hardening plastic surfaces by evaporating various materials in a vacuum were carried out at Polaroid. Considerable work was also done at Polaroid on cross-linked plastics which are much harder than CHM and styrene, but which present greater difficulties in the casting of accurate surfaces. The future trend in optical plastics seems to lie in this direction, but extensive experimentation will almost certainly be required. Success of commercial efforts to achieve a complete solution of the problem will insure that lenses and prisms of good quality will be available soon. As soon as surface hardness can be combined with good surface accuracy, and without the sacrifice of the present excellent internal homogeneity, optical plastics will immediately find many useful applications, partly due to reduction in weight and partly due to possible reduction in cost if they are produced in large numbers.

The strain in cast elements of CHM and

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styrene usually amounts to about 100 mμ which is not enough to limit optical performance in most optical designs of short focal length. The temperature coefficient of the index of refraction of both materials is high and this leads to a considerable change in focal length with temperature. Some systems have been "athermalized" by the addition of a glass element which contributes a large part of the positive power, while the plastics supply the corrections. The overall system has a reasonably constant focal length in spite of temperature changes. Even this procedure cannot prevent poor optical performance when there are temperature gradients within the system.

A considerable number of optical instruments incorporating plastics was designed for special military applications. One of the most successful of these was the T-108 antitank telescope (Project OD-128), with 3× magnification and an exit pupil approximately 1 in. in diameter. A plate-glass mirror erecting system, mounted in low-melting alloy, was used in this telescope. Another significant design was that for a 7-in. $f/2.8$ aerial camera lens for night photography. This camera lens incorporated four plastic elements and one element of DBC-1 glass to athermalize the system. An $f/0.7$ camera lens, for photographing radar screens, was designed with six glass elements and an aspherical plastic plate. Several collimators for reflex sights and a number of special telescope systems were developed and tested by the Services. At the end of the contract, many samples of plastic elements and of complete instruments incorporating plastics were transferred to the Naval Research Laboratory.

A considerable variety of optical techniques was developed under Section 16.1 of NDRC, partly in the natural course of developing specific equipment for the Services, and partly to develop new methods as an aid in the production of critical items.

Methods for grinding and figuring large lenses with high precision were devised at Harvard. Diamond milling was used extensively to save time in getting the glass ready for the fine-grinding operations with silicon carbide and emery. The edges of large lenses were ground with spherical surfaces to improve the fit in their cells and to facilitate assembly. Every effort was made to machine the cells to close tolerances and to mount the elements in such a way that they would be both accurately defined and free from strain. Spacer rings were lapped in many cases to give the best optical performance. The Harvard reports contain many descriptions of optical and mechanical techniques which will be useful in other optical shops.

A method for making roof prisms was developed at the Mount Wilson Observatory to help meet the heavy demands on the industry for prisms which must have the roof angle accurate to within a very few seconds of arc. A No. 11 Blanchard grinder with cup-shaped Norton diamond wheels was used. The glass blanks were waxed to special jigs. These jigs were so designed that the angles were established by turning the blanks first on one side and then on another side while they were in contact with a magnetic chuck on the rotating table of the grinding machine. The rate of feed was controlled and stopped automatically at the correct point. In this way, the prisms were milled in a series of carefully planned steps, using 100- and 180-grit diamond wheels. The average errors in the 90-degree roof angle of the milled prisms, measured with an air-pressure gauge, were usually less than 10 sec of arc. The variation in errors produced by individual jigs was less than this. It seems clear that angles could be milled with an accuracy of at least 5 sec of arc if necessary. Present methods of blocking glass for polishing introduce errors of about 30 sec. The prisms were polished on one side and then contacted to a plane-parallel block of glass, two on each side. The resulting unit was mounted in a metal cage and polished. Errors in the roof angle were observed with a collimator and eliminated by changing the location of a weight on the periphery of the cage. Milling operations required an average of 2.9 man-minutes per prism. The time for fine grinding and polishing was somewhat less than 1 man-hour per prism. It seems clear that one shop could mill enough prism blanks to supply the entire industry of this country in wartime.

A method for glass molding was developed at the Eastman Kodak Company to explore the

possibility of producing large numbers of lens elements with the minimum of skilled labor. A press with stainless steel molds, maintained at specified temperatures and operating in a hydrogen atmosphere, produced surfaces which were entirely free from orange-peel characteristics and which had accurately reproducible curvatures when cane or Pyrex glass was used. Thickness could not usually be adequately controlled to meet most specifications. Accordingly one surface was molded and the other was finished by usual methods. If optical glass is to be molded satisfactorily, an automatic machine will be required for preheating pellets of the correct weight, feeding them to the press at the correct temperature, and then conveying them through an annealing oven. A large number of aspherical lenses for the Fly's-Eye sight were made by this process with complete success. The process is particularly well adapted to making aspherical surfaces in production.

Photographic methods for making reticles were studied by the Edward Stern Company and the California Institute of Technology, under Project NO-98. These included four methods developed by the British Scientific Instrument Research Association, one developed at the Eastman Kodak Company, and one developed at the California Institute of Technology. It was hoped that some of these methods might be used to supplant mechanical methods. While the photographic processes were found to be more rapid than the conventional mechanical processes which employ pantographs, hand retouching was almost always required. The reproduction of complicated patterns was therefore more time consuming than the reproduction of simple patterns. Patterns involving both wide and narrow lines are particularly difficult to reproduce mechanically. Photographically this was also the case, although the time was less than with the mechanical process. The photoetching process was used to a considerable extent commercially during the war. The lead-sulfide process was also used for certain purposes. It seems likely that if the photographic methods are developed somewhat further they will find much wider applications.

Methods for depositing low-reflection and high-efficiency films on glass were studied and developed at the University of Rochester, at the California Institute of Technology, and at Vard, Inc., under Projects CE-9 and NO-97. Experiments with multiple coats were carried out to investigate the possibility of achieving more efficient low-reflection surfaces than those ordinarily deposited. Experiments carried out at the California Institute of Technology showed that quartz can be evaporated onto silver coats and offers substantial protection against tarnishing, but that when quartz is evaporated from tungsten coils it dissolves enough of the metal to lead to considerable absorption of light. Evaporation from iridium is indicated, but is not easy to carry out experimentally. A high-efficiency high-reflecting film can be deposited by fuming titanium dioxide onto glass. Such films can also be made very effectively by depositing alternating layers of titanium dioxide and cryolite or by depositing alternate layers of zinc sulfide and cryolite. These films can be designed to split a beam in such a way that the transmitted and reflected beams are almost equal in intensity, with little loss by absorption.

In response to a wide variety of Service requests, many new designs for optical systems for telescopes and binoculars were developed by the University of Rochester, the Yerkes Observatory, and the Bausch and Lomb Optical Company. One of these programs involved the design of binoculars and monoculars for use at night, under Projects AC-26 and CE-8. Apparent fields up to 70 degrees, and in one case up to 90 degrees, were already available in some commercial instruments. These designs were improved at the University of Rochester and applied to a considerable number of instruments for special purposes, including in particular the 6x42 antioscillation mounted binocular for use in the P-61 aircraft (see Chapter 14) and a 3x21 monocular with excellent definition over the whole field. A Schmidt erector system was developed for use with these wide-field telescopes. Coating of the surfaces eliminated the ghosts which are ordinarily troublesome in these erecting systems. The straight-in-line design makes the overall unit very compact. These night binocular and monocular systems all had 7-mm exit pupils and maximum

fields. In addition, eye relief was made as great as possible, so that the systems could be mounted on antioscillation units without the eyebrows of the observer touching the eye lens. A monocular with 85-degree apparent field using an aspherical plate in the eyepiece was developed. A commercial production model of a 7x50 binocular, with 10-degree field, was designed by Bausch and Lomb and was procured in considerable number for the Bureau of Aeronautics. Although this instrument was heavier than the Zeiss Deltar binocular, in proportion to the dimensions of the optical elements, it was better adapted to American methods of manufacture. Bausch and Lomb also made up two special binoculars for use in the testing program under Project NO-210. One was a binocular with 10-mm exit pupil, made by scaling up the standard Kellner eyepiece on the 7x50 instrument. The binoculars became 5x50, with the same field as the 7x50. The other special instruments were "dummy" binoculars, which consisted of the bodies of standard 7x50 instruments with the objectives and eyepieces removed, and with rhomboid prisms substituted for the Porro prisms to prevent inversion of the image. Three dummies were used with a series of diaphragms directly in front of the eye to determine the effect of exit pupil on binocular performance at night. This avoided the many complications which enter when magnification and the other effects of the optical system are present. A pressure-proof binocular was developed under Project NO-127 for use on the deck of a submarine. This binocular is linked to a torpedo director. It employs a heavy metal casing, capable of withstanding considerable pressure under water, with glass plates before the objectives and behind the eyepieces of the standard 7x50 optical system.

Four doublet objectives for telescopes and collimators were designed at Harvard in the course of work on various projects. They employ BSC-2 and DF-2 glass and form a significant series with varying degrees of correction. The design data, which is given in Chapter 10, should be of interest to experimental laboratories.

A revision of the design of the T-76 ($3\times$) and T-44 ($5\times$) tank telescopes was requested under Project OD-119. The principal aberrations of these systems were spherical aberration, color, and curvature of field. In view of the urgent need to get a satisfactory telescope into the field at the earliest possible moment, the problem was approached simultaneously by two groups, from different points of view. The University of Rochester designed an achromatic plate and new doublets for the erector system, which eliminated color and most of the spherical aberration, but could not change the curvature of field. A redesign of the erector doublets later permitted elimination of the achromatic plate. This solution of the problem seemed very satisfactory, since no change was made in the triplet objective or in the Erfle eyepiece, and would therefore cause the minimum of interference with production which had already started. In the case of the $5\times$ telescope, it was necessary to redesign both the erecting system and the objective to get satisfactory performance, while retaining the original Erfle eyepiece. The Yerkes Observatory undertook a complete redesign of the $3\times$ system. A widely separated Cooke triplet, with the entrance pupil in the middle of the objective, was used. The focus of the objective is 0.3 in. in front of the collective lens, so that the angular aperture of the bundle is reduced and the principal ray is bent and strikes almost centrally on the erecting system, which consists of two separated doublets each with a negative lens in front. The overall system is well corrected, but no attempt was made to limit flexibility by correcting each subassembly separately. Spherical aberration is well corrected at the reticle, but astigmatism is overcorrected there in order to compensate for negative astigmatism in the eyepiece. All aberrations in the T-93 telescope were much reduced in the final model which was submitted to the Frankford Arsenal. In the meantime, improvements in the T-76 and T-93 telescopes had also been made at Frankford, and these, rather than the NDRC designs, were finally adopted for production. Several commercial firms also submitted designs and some were adopted for limited production. A full study of the present status of designs for wide-field tank telescopes with large exit pupil is indicated. Present require-

ments demand not only a wide field and 7-mm exit pupil, but also that the optical system fit the 2-in. tube which is in current use. A careful study should be made to determine just how far the optical requirements can be met when this final condition is imposed. If a satisfactory result cannot be achieved when the tube is limited to 2 in. in diameter, then consideration should be given either to increasing the tube slightly or else to reducing the field or exit pupil somewhat, if it is deemed necessary to provide good definition over the entire field. Only tests under service conditions can answer this question.

A split-field tank telescope (1.5× and 5×) was developed in connection with Project OD-180 to provide simultaneously a relatively wide field with low magnification for finding the target, and a more limited high-power field for aiming. The field is divided along a diameter. Many unusual problems in design are involved, which are fully described in the Yerkes report (see Reference 7 of Chapter 10). Two objectives (telephoto and inverted telephoto) are used with two semicircular collective lenses and a common erecting system. The exit pupils for the two systems are circular and coincide. This telescope was examined by various groups and has been delivered to the Frankford Arsenal for further study.

Two antitank telescopes were developed. One of these was the T-118 plastic antitank telescope (5×) which was designed and constructed by Polaroid under Project OD-149. The aperture is 4 in. in diameter, with a mirror erecting system. The exit pupil is 20 mm in diameter and the eye relief 4 in. Performance is excellent. All of the lenses are plastic, except for one protective lens of glass at the front. The other telescope is a split-field antitank telescope (1.5× and 5×), which was developed under Project OD-180. The Ordnance Department had requested that the T-118 telescope be modified, with as few changes as possible, to provide two fields with differing magnifications. A specific layout for the design was proposed, but studies indicated that it would not give satisfactory results. Accordingly, a somewhat different approach was followed, involving the use of two mirror erecting systems. This design requires two holes in the armor in front of the objectives, but no greater area of exposure is required than for the T-118, or than would be required for the same exit pupils in the design proposed by the Ordnance Department. No model of the Yerkes design has been made.

A periscopic binocular (T-9) for use by tank commanders was developed by the University of Rochester under Project OD-129. The optical system was 7x50 with wide field. A common prism at the top of the instrument turned the beam downward, and could be replaced if damaged in its exposed position. The objectives were placed in the vertical beam and were followed by three reflections in glass. The Frankford Arsenal originally requested that provision be made for a unit-power system between the two telescope systems, but later asked that this be eliminated. However, after a model had been completed at the University of Rochester, it was decided that the unit-power system should be restored. Accordingly, the mechanical parts were redesigned by the Arsenal for production. The instrument gave excellent optical performance over the entire field.

A precision theodolite telescope was developed by the University of Rochester under Project CE-21. The final design employs an air-spaced triplet objective of 40 mm aperture and 122 mm focal length. The telescope is inverting and is focused internally by moving a negative lens. An orthoscopic eyepiece is employed. The system is anallatic to 1 per cent, from 3 m to infinity. A sample showed optical performance at least equal to that of a Zeiss telescope of similar type.

An extensive study of the optical properties of submarine periscopes was carried out at the Yerkes Observatory. This work began as a natural continuation of Project NS-242 which covered quick developing equipment for periscope photography. In the course of that work, it had been found that the optical performance of the standard submarine periscopes left much to be desired, particularly in the case of the models which employ small lenses at the upper part of the system. By replacing one of the doublets in the erector system by a quintet, which included two elements of optical fluorite, the color correction of each of three periscopes

was considerably improved. Two-thirds of the whole color defect arises in the erector system of these instruments. A model of this correcting unit for the 1.4-in. periscope was made at Harvard. The monochromatic performance is slightly inferior to the original design, but the color has been markedly improved so that it should be possible to utilize a much wider region of the spectrum photographically, thus reducing exposure time and diminishing the deleterious effects of image motion. Tests of the corrector were carried out under a Navy contract after the work at Yerkes had been completed. The results did not come up to expectations, but time did not permit an investigation of the reason for the discrepancy between the results of ray tracing and of photographic resolution tests. In the case of the 1.4-in. periscope, better results would be achieved if both erectors were replaced by simpler fluorite units than by using the single complex unit that was actually designed. In the case of the 1.9-in. and the Type IV periscopes, for which the optical systems are simpler, designs have been worked out for air-spaced doublets of BSC-1 glass and fluorite which replace both the doublets in the standard erector system. In these two periscopes the objective and eyepiece contribute little to the secondary color. The use of fluorite seems entirely practical for these two periscopes at least, and it would be desirable to have models of the Yerkes correctors made and tested. An eyepiece with longer eye relief was designed for the 1.4-in. periscope.

Field-flattening camera lenses were also designed for the 1.4-in. periscope, both in its original form and when the fluorite corrector and long eye relief eyepiece have been substituted. It is to be expected that these camera lenses would give much better performance off axis than the usual camera lens because of the striking curvature of field which exists in the periscope. In the case of the 1.9-in. periscope, a field-flattening lens can be installed within the camera, just in front of the film. It would reduce the present confusion disk, 3 degrees off axis in object space, from 0.09x0.11 mm to 0.01x0.01 mm when a yellow filter is used. A similar lens can be used with the Type IV periscope, but no filter is required, even without the fluorite corrector. Serious consideration should be given to redesign of the entire periscope systems to reduce color and to flatten the field as far as possible within the allowed dimensions of the tube.

A unit-power aircraft periscope, to be used by an observer in TBF aircraft with linkage to other equipment, was designed at the Yerkes Observatory under Project NR-111. Four identical doublets were employed to facilitate production. A model was made at Harvard and successfully tested at Quonset. The optical parts for sixteen additional models were made at Harvard and turned over to the Navy. Experiments were later tried with the optical system of the 3× tank telescope designed at Yerkes. This was mounted as a periscope, with a prism ahead of the eyepiece. It was decided, as a result of these tests, that 2× magnification would be most suitable. The Bureau of Ordnance undertook the design of a periscope with this magnification.

A periscope for the P-51 aircraft to increase the vision of the pilot downward was designed at Yerkes, following a suggestion made at Mount Wilson. The periscope is 110 in. long, with unity magnification. The lenses, which are about 8 in. in diameter, could be made of plastic. The eye lens would be incorporated in the windscreen in such a way as to cause minimum interference when the pilot turns from looking through the Plexiglas to looking through the eye lens. The pilot can ordinarily see downward only about 3.5 degrees. A periscope 110 in. long would increase the downward view to more than 20 degrees. Such a periscope would be useful, and apparently practical, if it turns out that the fuselage cannot be redesigned to give the same result. In any case this system has attractive possibilities for use with a reticle attached to a lead-computing mechanism. The large aperture, the use of an opaque reticle, and the elimination of a reflex plate are all advantages.

A foxhole periscope was designed on the basis of an informal request from the Signal Corps. The purpose was to enable an operator in a foxhole to watch the operation of a motion picture camera on a support just above the

edge of the hole. The Yerkes Observatory designed two unit-power systems which could be used as viewfinders for the camera, with 18-in. offset, 40-degree field, and eye reliefs of 1.6 and 2.0 in., respectively. The exit pupils were 7 and 10 mm in diameter, respectively. Samples of these instruments were made up by the Signal Corps, and gave satisfactory performance.

A viewfinder for the P-80 aircraft was studied by the University of Rochester in connection with Project AC-131. The viewfinder was to be used in the photographic version of this aircraft to permit the pilot to guide his course over the target and to make exposures at the correct time. It was requested that this viewfinder be periscopic, with a 45-degree field of view and a 5-in. exit pupil. An unobstructed vertical view was desired, if possible. An optical system was worked out tentatively but was not fully designed because the many problems relating to interference with mechanical parts could only be settled by mutual discussion at the factory. The University of Rochester system employed one-quarter magnification. It is likely that this would be a serious disadvantage for a pilot at high altitude, since it would make identification of targets difficult. A better solution might be to provide a screen of considerable size on the instrument panel, on which a unit-power image would be projected by a periscope with large lenses and a scanning prism at the lower end.

A wide-field projector for a dome trainer was developed for the Bureau of Aeronautics under Project NA-200. A field of 180 degrees horizontally and 90 degrees vertically was desired, with a relative aperture of $f/2$. The Yerkes Observatory developed a system which met the requirements by using a 6-element Petzval-type lens with a field of 14 degrees in combination with a convex spherical mirror 12 in. in diameter, which increased the field by a factor of ten. The mirror has little effect on spherical aberration and coma, and no effect on chromatic aberration. The curvature of field of the mirror is opposite in sign to that of the lens, and they are made to cancel one another in this respect. By placing the observer slightly in front of the projector and enough to one side to miss the beam, the apparent field is increased to 180x90 degrees. Definition is entirely adequate. Some distortion is inherent in the system. This would be nearly entirely removed if the same optical system were used as a camera lens for taking the training exposures. The lens was tested successfully by the Special Devices Division of the Bureau of Aeronautics and was transferred there.

A high-resolution projection lens was designed at Yerkes for use at Dartmouth in the binocular testing program. In this case the requirements were very different. It was merely necessary to project a small target at the center of the field, but it was extremely important that resolution be almost perfect, so that the amount of light scattered into the image of even small targets would be insignificant. The Yerkes Observatory designed for this purpose an $f/9$ lens which was a cemented doublet corrected for 5,461 A, bringing F and D nearly together. This was done to give the best performance with the eye, which has maximum absolute sensitivity at low levels near 5,060 A. The effective wavelength for maximum sensitivity shifts toward the red when tungsten illumination is used, and is located at about 5,330 A. Four of these lenses were made in a commercial shop. Some of them were refigured at Harvard to give the best possible performance.

A plastic condenser lens was made at Harvard for photoelectric work. The diameter was 8 in. and the relative aperture $f/1.5$. Spherical aberration was reduced to a point where, in spite of the fact that no color correction was undertaken, the circle of confusion was only 3 mm. This is entirely adequate for most condenser applications. If this lens were produced in large numbers the elements could be molded (see Chapter 8).

A coronagraphic objective was designed and made at Harvard for use under a Navy contract. A cemented triplet with good color correction was employed. Great care was taken to reduce scattered light to the absolute minimum by eliminating all possible scratches. The lens was designed as a triplet so that all outside surfaces, which are necessarily exposed to dust and cleaning, would be of crown glass.

Reflex sights were used extensively during

World War II for many applications. They make it possible to project a reticle pattern at infinity with considerable eye freedom and with minimum obscuration of vision. Most of the applications with which NDRC was concerned involved sights for aircraft, where the ideal is a sight which does not require the pilot to locate his eye closely in a special position and which occupies the minimum of space. An almost ideal arrangement would be to reflect the collimated beam from a large aperture on the bulletproof glass. Steps were being taken in this direction at the end of World War II.

The Yerkes Observatory made a general study of collimators for reflex sights, and established what could be expected from two-, three-, and four-lens systems. Models were made for testing and demonstration. These have been transferred to the Armament Laboratory at Wright Field. A sight in which the light path is folded twice by reflection, so that it assumes a "Figure-4" arrangement and is extremely compact, was developed at the University of Rochester. This design was developed for production by Bell and Howell under direct Army contract. The University of Rochester also developed a lens-collimated reflex sight for use with the M-7 computer on the 40-mm Bofors antiaircraft gun, under Project OD-146, to replace the small aperture unit-power telescope which was hard to use. Three models were made, each with a half-reflecting reflex plate. Sky illumination is employed in these sights in the daytime, using a region near the target. At night, electric illumination is available. On one model, a radium-excited phosphor is used to provide the auxiliary illumination. For use on the M45 multiple machine-gun mount, wide-field sights to cover leads up to 280 mils were designed at the University of Rochester and at the Yerkes Observatory. A similar design was later used for a sight on a pantograph mount to be attached to the machine gun on a half-track truck. Two collimator lenses for various applications of reflex sights were designed at Mount Wilson. A special sight, known as the *flight sight*, was developed by the University of Rochester (Project NO-103) to permit the pilot of an F4U-2 airplane to see reflected in the reflex plate and collimated at infinity not only the reticle, but also the radar pips, the air-speed indicator, and the gyro horizon. Tests indicated that this device is capable of assisting the pilot of a fighter plane to a very considerable degree in making a radar approach on a target at night. A sight with plastic lenses, having 3.5 in. aperture and operating at $f/1.6$, was developed by Polaroid to replace the Navy Mark 8 sight. The optical system was folded with one reflection and mounted in a magnesium housing. Four models were made and tested by the Navy and the Army but none were produced, because of the increased availability of glass lenses.

The Lens-Mangin sight was developed at Yerkes to provide a large exit pupil. This sight is unusually compact. A model with 4x6-in. aperture had dimensions only 6.2x6.5x7.5 in., exclusive of the reflex plate. Light from the reticle is reflected by a 50 per cent dividing plate to a Mangin mirror which returns it through the dividing plate to a lens and the reflex plate. The usual Mangin system is well corrected for color and spherical aberration, but not for coma. The addition of the weak lens controls coma and leaves only astigmatism as a significant residual aberration. This is not present in a serious amount. At best, only 25 per cent of the light from the reticle can reach the reflex plate, because of the double passage through the dividing plate. This is the only serious disadvantage of this highly ingenious sight and it seems likely that it can be overcome by giving adequate attention to the illuminating system. The fact that a large aperture is available in very limited space, with the use of only two simple lenses, makes this design worthy of further study.

The Bowen sight represents another unusual design, intended to provide large aperture without obstructing the pilot's view. The reticle is collimated by a large spherical mirror. A diaphragm on the illuminating system is placed at the center of curvature of the mirror, and is focused, after reflection at the reflex plate, to form an exit pupil at the pilot's eye. Within the region of this pupil, the pilot sees the collimated reticle over a field which is limited only by the size of the concave mirror. The magnitude of the spherical aberration, which is the

only aberration in this system that produces parallax of the reticle, depends on the diameter of the diaphragm of the illuminating system, and its reflected image of equal size, the exit pupil. When the aperture of the illuminating system (and of the exit pupil) is equal to one-quarter the radius of curvature of the mirror, that is, when the aperture ratio is $f/2$, the maximum aberration, which occurs when the eye is at the edge of the exit pupil, amounts to about 1 mil. The size of the reticle does not affect the magnitude of the aberrations. This is a unique property of the Bowen sight. The best disposition of the parts of the sight raises problems which depend on the design of individual cockpits. Two models have been made: one for the AT-6 airplane, where the mirror was placed above the line of sight and the reticle and illuminator below; the other for the P-51 airplane, where these locations were reversed. In each case the supports which connect mirror and reticle were designed to lie in front of divisions in the plastic of the canopy, so that there was little interference with normal vision. Pilots expressed great interest in this sight, particularly because of the generous eye freedom which it allowed, and because the two eyes could view the reticle simultaneously.

A third design, which provides large aperture within compact dimensions, is that of the Fly's-Eye sight, which was developed at the Eastman Kodak Company, under Division 7 of NDRC, for use in fighter aircraft. Many small reticle-collimator units are grouped together, in a hexagonal array, accurately aligned with one another so that when the eye moves across the combined aperture the reticle appears to maintain a steady position at infinity. Simple aspherical lenses were used, molded by the process described in Chapter 9. The reticles, which were made by etching sheet metal, were mounted on an Invar plate and located in the correct positions. Two models were made with apertures $4\frac{1}{2}$x$5\frac{1}{2}$ in. The illuminating systems consisted of six concave mirrors cut to square dimensions, approximately 2x2 in., so that they would fit together at the edges. One frosted electric lamp was used in each mirror. Air was circulated by means of a blower to cool the unit. The collimated beam from the multiple lenses was reflected from the armor glass. This made it possible to mount the sight ahead of the instrument panel in a position where it did not interfere with other equipment. From the pilot's point of view the installation was highly satisfactory.

Two solid glass sights were designed at the Mount Wilson Observatory. One of these was intended for experimental use on an M-1 Garand rifle to aid men on the ground in replying to strafing fire from aircraft. This application requires a sight with large rings to estimate the lead. A solid glass block with an air Mangin lens at the lower end, and with a diagonal cemented surface coated for half reflection, was used. The aperture was $\frac{5}{8}$x$\frac{5}{8}$ in. The reticle was cemented to a small prism at the upper end. Sky illumination was sufficient to give a satisfactory display under most conditions. A quarter-wave plate was incorporated just in front of the Mangin reflector to reduce light loss which resulted from polarization at the inclined half-reflecting interface. The sight gave good performance, although the requirement for using the M-1 rifle against aircraft was never fully established. A model is being transferred to the Antiaircraft Service Test Section, Ground Forces Board No. 1 at Fort Bliss. The second sight was similar in construction, but was designed to fit the Bureau of Ordnance gunsight Mark 17. Tests showed that it was undesirably heavy for this application, in spite of the fact that the aperture was only 1x1 in. The model of this sight was also transferred to Fort Bliss.

Three models of stadiameters were developed at the University of Rochester, primarily for use in aircraft. When the distance of an object is measured with a rangefinder, the result depends on measuring differences in apparent direction at the ends of a known base line, whereas when a stadiameter is used the apparent angular size of an object of known dimensions is measured, from which the distance can be calculated. Although rangefinders have the advantage that they require no information about the size of any object, they are large, cumbersome, and expensive, which seriously restricts their usefulness. Stadiameters are small and inexpensive, but they do require

knowledge of the size of the target. In many applications where this is known, they have proved to be extremely convenient. Moreover, no accurate aiming of the instrument is necessary, as with coincidence rangefinders. It is merely necessary to have the target somewhere in the field. A unit-power stadiameter was developed originally to assist the pilots of aircraft to maintain a specified separation from one another in a certain tactical maneuver. The wing span of the leading plane was of course known. The optical system consisted merely of two flat mirrors, approximately parallel to one another, with a half-reflecting half-transmitting coat on one of them, and a fully reflecting coat on the other. The latter was mounted on a pivot with a tangent screw and divided drum to permit making small adjustments in the angle between the two mirrors. By looking through the half-reflecting mirror, the observer sees a double image of the target and sets the angle of the other mirror until the two images just touch. Settings can be reproduced to at least 0.5 mil. The zero point is set on a distant object.

A 3× stadiameter was developed at the University of Rochester to aid F-5 (P-38) pilots in maintaining a separation of 6 miles while flying parallel mapping courses. At this range some magnification was essential. A 3× wide-field system is used, with a mirror-prism erecting system in which is incorporated a beam splitter bringing in light which has passed through a variable angle prism. Color is not serious up to about 50 mils separation. The field is 23 degrees, of which 18 degrees can be deviated and used for stadiametric setting. The exit pupil is 7 mm. The setting of the variable angle prism, which consists of a plano-convex and a plano-concave lens, is controlled by a tangent screw with a divided head reading to 0.1 mil with a vernier. Settings can be reproduced to 0.1 mil.

There is need for a quick means for setting range into the fire-control system of the B-29 aircraft. Under Project AC-114, a double-image stadiametric attachment for the pedestal sight was devised, based on the use of two plane mirrors close to one another and nearly parallel. The first mirror reflects approximately one-third of the light to give a fixed image, while it transmits nearly two-thirds of the light to a fully reflecting mirror which can be adjusted in angle and which reflects a second image through the first mirror. The two images are brought edge to edge by turning a knob. It seemed likely that this device would facilitate rapid ranging, since it would not be necessary to have the target in any particular part of the field. The optical parts and the layout for the stadiameter were turned over to the General Electric Company.

In connection with the problem of night interception of bombers by fighter aircraft, a need arose for aids to night vision. Under Project AC-26, the University of Rochester developed wide-field binoculars (see Chapter 10) with 7-mm exit pupils. The use of these binoculars in aircraft was limited by the effects of angular vibration which were greatly magnified by the binoculars. Accordingly, studies of methods to eliminate angular vibration in optical instruments were undertaken. Linear vibration is much less serious. Antioscillation mounts of different types were developed by the University of Rochester, the Eastman Kodak Company, and by the Technicolor Motion Picture Corporation. The first of these was a ball-bearing gimbal mount with the center of gravity of the instrument set accurately at the intersection of the two axes of rotation to prevent the conversion of linear into rotational vibration. Damping was provided in each coordinate by air dashpots. This mount was tested extensively in aircraft. It was found possible for a pilot to fly an airplane at night while overtaking a target plane and while looking steadily through the glasses. The effect of magnification is to make the approach seem far more gradual than it really is, but experience enables the pilot to make due allowance for this and to pull out in time to avoid a collision. A production model of this antioscillation mounted binocular was developed by the Eastman Kodak Company. These instruments were standard equipment in P-61 night fighter aircraft. The binocular is mounted on a track at the left side of the canopy where the pilot can reach it when radar indicates that a target is ahead. The binocular is carried on a carriage with a hinge

that permits the instrument to swing out into place in front of the pilot, with provision for locking temporarily to the top of the armor glass frame. An illuminated reticle is incorporated in one half of the binocular, which can be used as a gunsight if desired. The instrument can be removed and stowed in less than 2 sec. Tests have shown that the 6x42 system increases the range of detection at night by a factor of about 4.5, so that an excellent transition is provided between radar and naked-eye detection. Images are very steady, even in the presence of marked aircraft vibration. Under Project NA-140, one of these binocular units was linked to other equipment by Section 16.5 of NDRC. Tests, made under Project OD-116, showed that an antioscillation mount is not needed when binoculars are installed on a stationary tank and are used with the engine running.

Antioscillation mounts for standard binoculars, also based on the center-of-gravity principle, but simpler in design, were developed by the Eastman Kodak Company and by the Technicolor Motion Picture Corporation. In both of these mounts the binocular is held at its center of gravity. The Eastman mount carries the instrument on a $\frac{3}{16}$-in. steel ball resting in a synthane cone, which provides freedom of rotation in three coordinates. A coiled spring surrounding this unit supplies the necessary restoring force, while dry friction between the ball and cone supplies damping which can be adjusted by changing the diameter of the ball. Stops are added to limit the motion. The center of gravity is maintained at the center of the ball, in spite of changing the interocular separation of standard binoculars, by providing a specially shaped cam on which the two sides of the instrument ride. A headrest and eye guards are added to aid in maintaining the proper relation of the eyes to the instrument. Several units were made for testing in aircraft. Several were also mounted in specially designed alidades for use on shipboard, under Project NS-105. The alidades were equipped with filters for linear vibration to reduce the effects of severe vibration on bulkheads, which often is converted into angular vibration even with a good antioscillation mount if the balancing is not very precise. Tests of these mounts in aircraft and on ships showed that they are capable of giving excellent performance at least comparable with that of the gimbal mount, although boresighting characteristics (at least in the absence of vibration) are not as good. The design is much simpler and less expensive, and requires less critical adjustment and servicing. For these reasons further studies and tests should be made to determine the extent to which it may be adequate for various applications. Wide-field binoculars could, of course, be mounted on this type of filtering unit.

The Technicolor mount is, in general principle, similar to the ball-and-cone mount described above. Standard binoculars are supported at the center of gravity, but in the Technicolor mount the instrument is carried on a post at the lower end of which is attached a ball $\frac{3}{8}$ in. in diameter, surrounded by two pure gum rubber washers, one above and the other below the ball. The rubber is enclosed by an outer split sphere which compresses it enough to provide the necessary restoring force. Damping is provided by spring shoes acting on the outside of the upper hemisphere with adjustable tension so that the damping can be varied. The outer hemisphere is carried on the base through a shock-absorbing unit which consists of a horizontal metal plate compressed between two sheets of sponge rubber. One model was designed for use in PBY aircraft, in the copilot's position, attached to the roof of the canopy either by rubber suction cups or by clamping to a rigid bar fastened to two ribs of the canopy. In either case the unit could be quickly installed or removed. Another model was designed for use on ships, with an alidade mount and windscreen. These models were tested in aircraft and on ships. In both cases they showed definite reduction in the vibration, as compared with rigidly mounted binoculars. Further tests will need to be conducted to compare adequately the performance of the Technicolor and Eastman mounts. It seems possible that the base filtering unit in the Technicolor mount impairs its performance under conditions where linear vibration is severe, since such vibration is converted into rotational vibration by the base unit which is located below

the center of gravity, and thereby increases the filtering required of the central antioscillation unit. Tests should be made to establish the effectiveness of the base filtering unit.

A precision phototheodolite was developed by the Eastman Kodak Company under Project OD-48. Many needs for such instruments were apparent, even before the beginning of World War II. These included the testing of heightfinders, testing the performance of the operators of heightfinders and rangefinders, construction of range and fuse tables for use with antiaircraft guns, construction of bombing tables, recording of aircraft motions, and finally testing the overall accuracy of fire-control equipment. Tests of the Askania instruments showed that they were almost, but not quite, capable of giving the 0.1 mil overall accuracy desired. Accordingly, the design of entirely new instruments was undertaken. Cameras with focal lengths of 12, 24, and 48 in. were provided. The 12-in. camera was equipped with a conventional lens, but for the cameras of longer focal length two-mirror achromatic Mangin systems were used. The primary mirror was pierced by a hole to transmit the beam from the secondary mirror to the focus which was just behind the primary. Although these cameras involved many complications relating to optical figuring of the achromatic components and relating to mounting the elements, they have the advantage that the overall length is less than can be achieved with telephoto lenses. In the case of the 48-in. camera, an $f/11$ lens of telephoto type was provided as an alternative in the event that any difficulty be experienced with the large Mangin camera. Thirty-five millimeter film is carried in a camera mechanism of the single-frame type, capable of operating up to 10 frames per second. For faster operation, the camera is run continuously at 20 frames per second. A series of neutral and color filters is provided close to the focus. Two-man tracking is provided. Dual-lead worms are used to reduce backlash. Azimuth and elevation are recorded by photographing drums and counters on the worm shafts, which are illuminated by Edgerton flashes at the mid-point of each photographic exposure. Screws on the base permit leveling one instrument and misleveling the other of a pair, to allow for the curvature of the earth. The instruments have been installed in domes, at the ends of a base line 11,000 yd long, at Fort Bliss, Texas by the Antiaircraft Service Test Section, Ground Forces Board No. 1. Extensive tests are being conducted to measure the accuracy of the instruments. These tests will include measures of the positions of fixed targets when tracking is being done at various rates and also measures of the positions of stars which provide targets accurately placed over a wide range in azimuth and elevation.

Optical scanning devices were developed under Section 16.1 in an attempt to improve the effectiveness of lookouts in searching for both aircraft and submarines. The purpose of these devices is to permit the observer, while seated in reasonable comfort, to look into fixed eyepieces and to scan systematically and with full coverage an assigned sector of sky or horizon. In all of the scanning devices, the optical path is caused to sweep, in one or in two coordinates, by rotating mirrors or prisms which in some designs are part of the telescope erector system and in other designs are reflectors added to standard binoculars expressly for the purpose of scanning. Four scanning devices which have been designed and tested appear to warrant further study and development. Carefully controlled tests are needed to determine the extent, if any, by which they increase the efficiency of lookouts in picking up targets, in comparison with hand-held binoculars. The relative effectiveness of monocular and binocular scanners of the same type should be determined after a headrest and eye guards to aid in locating the eye have been added and maximum comfort provided to make the use of the monocular type as effective as possible. Antivibration mounts should be used with binoculars in scanning devices on shipboard, and experiments should be undertaken with stabilized scanners. One of the most promising models should be provided with azimuth and elevation indicators in the field of view and with remote indicators actuated by selsyn linkages. Consideration should also be given to connecting a scanning device directly to the fire-control system. The importance of the lookout problem justifies active work along all these lines.

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An antiglare shutter, intended to protect the dark adaptation of the pilot of a night fighter aircraft in the presence of blinding flashes which might be discharged by a pursued bomber, was developed by the Eastman Kodak Company as part of the program on night vision devices under Project AC-26. The use of binoculars greatly increases the likelihood that dark adaptation will be destroyed by any flash, because of the greatly increased amount of light which enters the eye from any point source. The shutter curtain is made of black nylon cloth with pure gum rubber cords cemented along the edges to insure quick opening. The driving force for closing the shutter over the apertures of the binocular is provided by an electrically fired charge of tetrazene, to which potassium perchlorate is added to oxidize the residue and prevent fouling the cylinder. The firing charge is loaded in small primer cups in a magazine which holds ten charges and is advanced automatically by a ratchet mechanism. The shutter is capable of closing the binocular apertures completely in about 0.0015 sec. A delay mechanism holds the shutter closed for 0.3 sec, after which it opens and is ready to close again in response to another signal. Stanford University developed a photoelectric control circuit which triggered a Thyratron tube so as to discharge a condenser through the primary of a transformer. The resulting surge in the secondary fired the tetrazene cap. The amplifier was designed to respond to a light pulse of 0.01 footcandle, which is about the intensity of the full moon. It was particularly free from microphonic effects. Tests of the amplifier in the P-61 aircraft showed excellent performance, but time did not permit testing the complete shutter and amplifier as a unit.

Rapid processing equipment for periscope photography was developed, under Project NS-242, by the Eastman Kodak Company. It is frequently desirable to take a photograph through the periscope which is exposed for the minimum possible time. If this photograph could be processed within a minute or less, it would be possible for several officers to examine and discuss the photograph, and to base tactical decisions on it, thus diminishing the need for visual examination of targets, and thereby reducing the total exposure of the periscope. A special back was developed for the standard 35-mm periscope camera Mark 1, which permitted the removal of short lengths of exposed film for transfer to a light-tight cassette which contained a knife for cutting the film, and was provided with light locks through which solutions could pass when the cassette was transferred to a processing tank. The film was held on a metal frame inside the cassette. After development and brief washing, the film was removed in its frame and examined in a special viewer which enlarged the image 3× by means of a concave mirror, while illuminated with a fluorescent lamp and ground glass. Both eyes can be used simultaneously with this viewer, which is convenient to operate. Special film and special developer were provided, which made it possible to view the negative in about 40 sec. Even under these conditions, resolution was comparable with that ordinarily given by Super-XX film. Tests on a submarine in the Pacific showed that the performance of the equipment was satisfactory and that the use of rapidly processed negatives was tactically desirable. Five units, each consisting of three processing cassettes, eighteen film holders, four processing tanks, and a viewer, were delivered to the Bureau of Ships for further tests.

Tests of resolution in periscope photography were made at New London on the USS *Pilotfish*, and also through a periscope mounted permanently in the optical shop at New London. A distant resolution chart, similar to those used for aerial photography (see Chapter 2), was mounted at a distance of more than half a mile. Through the 1.4-in. periscope the 50-mm camera resolved only about 16 lines per mm without filter. Chromatic aberration and curvature of field were shown to be the principal aberrations that limited resolution. A yellow filter helped considerably. A camera lens to correct the curvature of field is described in Chapter 10. A 72-in. focus glass-fluorite collimator with a point source at the focus was designed and constructed at Harvard for testing periscope performance on a quantitative basis over the whole field, and at a wide variety of focal settings. Resolution targets could be introduced for testing photographic performance. This collimator

has been transferred to the National Bureau of Standards. It seems clear that marked improvement in periscope photography can be realized if the optical systems are improved. Only a first step was taken by the Yerkes Observatory in designing glass-fluorite elements to replace one or both of the present erector doublets (see Chapter 10).

A two-star navigating device has been developed to provide the observer with a direct display of his position at any moment. The instrument is set in advance so that, if it were located with its base level at any selected target, the intersection of two astigmatized star images would be at the center of a reticle. If the intersection of the star-image lines is held at the center of the reticle when the instrument is at any location other than at the target, the distance and direction of a spherical bubble from the center of the reticle indicate directly the distance and direction to the target. The reticle might even show a faintly illuminated map. If the instrument were stabilized, so that the base were maintained always level, then the intersection of the two star-image lines would indicate directly the location of the instrument on the surface of the earth, without the need for guiding, except approximately in azimuth. In either case, some averaging would be required to eliminate the effects of linear accelerations due to the aircraft. A preliminary model shows that the general design is practical, but that considerable further development will be required.

Chapter 1

EQUIPMENT FOR AERIAL PHOTOGRAPHY

By *James G. Baker* and *J. S. Chandler*[a]

1.1 INTRODUCTION

THE NEED for resolving the finest possible detail on aerial photographs taken for reconnaissance purposes over enemy territory was recognized early in the war. In October 1941, the Army Air Forces requested the National Defense Research Committee [NDRC] to undertake, as part of Project AC-29, the development of high-resolution lenses. This included not only a request for the development of lenses of long focal length but also lenses of relatively short focal length with wide angular coverage. The greater part of these developments was carried out at Harvard University under Contract OEMsr-474, but two Schmidt cameras were developed at the Mount Wilson Observatory under Contract OEMsr-101, and one lens for night photography was developed under Contract OEMsr-160 at the University of Rochester. The laboratory testing of aerial lenses, both standard types and NDRC prototypes, was conducted at Mount Wilson under Contract OEMsr-101 and at the Eastman Kodak Company under Contract OEMsr-392. Early in 1945, the facilities at Harvard were greatly expanded to permit carrying out the extensive flight testing program described in Chapter 2, as well as to make it possible to complete prototype models of several important lenses in the shortest possible time.

It is generally agreed that for purposes of aerial photography a lens system should be designed at the optimum aperture to produce images which are unvignetted, within the Rayleigh limit, and located on an undistorted focal plane flat to the corners of the adopted film size. However, practical considerations, as well as limitations imposed by nature and by present technology on image quality at a given lens speed and coverage, cause such drastic departures from the ideal that many differences of opinion have arisen as to the characteristics of the best compromise.

A perfect image within the meaning of diffraction optics is rather easily understood, in so far as applications to aerial photography are concerned. It is certain that, with due allowance for statistical variations, a photographic emulsion will react in a predictable fashion to a perfect optical image falling on its surface. Resolution patterns of any adopted kind at any given contrast can then be used to arrive at a quantitative number representing the resolving power of the emulsion under such conditions.

By restricting aperture, focal length, angular coverage, and range of color correction, the optical designer could for a given type of lens system produce images unvignetted over the field and within the Rayleigh limit. Various lens systems would be judged for quality thereafter on how far the several frontiers have been pushed for a given light intensity on the emulsion, dependent on *f*-number and efficiency. Moreover, systems might differ widely in economy, ease of manufacture, utility, and general bulk.

Lens designers in general have been forced by competition and by practical considerations to work on more ambitious lens systems, with aberrations quite appreciably outside the Rayleigh limit. Herein enters a host of considerations governing the character and magnitude of the inevitable residual errors. Practicality relative to mass production of aerial lenses again demands that the simplest, most easily made lens system be adopted, within the appropriation and facilities that can be allotted to achieve a certain result.

Military needs are so inherently wasteful that for specialized lenses the designer is given

[a] The material for this chapter has been compiled primarily by Dr. Baker of the Harvard College Observatory. Dr. Chandler of the Eastman Kodak Company has compiled the section on Antivibration Mounts for Aerial Cameras (see Section 1.6) with the exception of the short articles on the "Center of Gravity Mount" (see Section 1.6.6) and "Rotating Prism Unit" (see Section 1.6.8).

a degree of freedom quite far beyond ordinary commercial practice. Economy, in so far as applied to aerial cameras, means little if the cost of the reconnaissance aircraft is far in excess of the cost of the camera it carries. Ends can be achieved by making up complex systems out of keeping with compromises based on salability to the public. However, unnecessarily complicated systems are undesirable since their mass production would prove an unwelcome drain on the usually inadequate optical facilities of a country.

On the other hand, military needs are also exacting. The designer soon finds himself in increasing throes of image aberrations with optical systems of increasing complexity, each more difficult and tedious to construct than its predecessor.

Standard lens systems are found to yield images of surprising size far off axis. The image of a point source in the focal plane is often as large as 0.4 mm, taking account of all light. The same lens, tested on the bench at high contrast, will often yield resolution of the order of 50 lines per mm on fine grain plates and visually might yield 150 lines per mm. What is to guide the designer?

Various persons have been heard to say that almost any reasonably good lens can take high-quality aerial pictures. Others have said that in practice it is not the lens that needs improvement but the conditions under which the lens is used. The latter problem is discussed elsewhere in this volume, but for present purposes has no material bearing on anything but the wisest limit of quality of the lens consistent with practicability. Because of such individual statements and beliefs, a great number of laboratory and aerial tests have been carried out in many laboratories and several countries.

The Americans have adopted almost without exception the testing of lenses at high contrast with a 3-line test pattern. The English and Canadians[1] have found that for purposes of aerial photography, low-contrast 2-line patterns and annuli are adequate and more meaningful than the high-contrast patterns. Various observers have found that the vast majority of ground objects lie in a brightness range of about 1/0.10 on a first-rate photographic day. In the presence of enhanced atmospheric haze, or in shadows of clouds or buildings, this contrast ratio drops very materially. The English and Canadians have concluded that the inherent contrast of aerial photography is low, and therefore that to test the effective performance of lens-film combinations for aerial photography realistically, a contrast of about 1:0.5 is desirable. The Canadians have also concluded that for aerial photography low-contrast test targets are more meaningful, both from the air and in the laboratory.

Most probably, the complete story is multidimensional and cannot be determined by any single choice of high or low contrast. The British choice more nearly fits the average facts, but also tends to conceal important improvements in peak performance of lenses and camera mounts. The American choice results in improvements that may be too expensive and elaborate for the average benefits gained. Moreover, the Americans run the risk of concluding that a lens system is better than it is, because of high-contrast work. The British and Canadians run the risk of falling behind American results on first-class photographic days.

Because of the completely independent German view presented, it seems of interest to reproduce at this point abstracts in translation of *Development Problems in Aerial Cameras* by H. C. Wohlrab.[2]

> There is reason to believe that the failure of enemy [i.e., non-German] photographic apparatus to exceed picture sizes of 13x13 cm. or 18x24 cm. respectively, is due not least to the lack of suitable high-power lenses. This appears to be confirmed by the circumstances that British cameras have frequently been captured equipped with German lenses dating back to the last war.
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> The demand for suitable long-focus lenses of course increases with still greater flying height, but development in this direction appears to be limited by the attainable precision of manufacture, since the lens is required to maintain the resolving power of a shorter focus lens, only the flying height and not the image scale being different. The difficulty becomes apparent already in the aerial production of 75 cm. lenses and increases incommensurably with further increase of the focal length.
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> The principal difficulty lies in the manufacture of the requisite optical glass. The production of glass for optical lenses is not a mechanized quantitatively controllable process. While out of a pot-full of optical glass many small pieces suitable for the manufacture

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of lenses can be produced, pieces of large size with the required absolutely uniform refraction and dispersion over the whole mass are few and far between. Apart from the fact that such large lenses are disproportionately costly, they are also very wasteful of materials and labor, since production of any considerable number of lenses of the required uniform refractive power from a single charge of glass is excessively difficult, while the slightest deviation from the prescribed standard involves complete recalculation of the corresponding lens.

The aperture of the lens is limited by the same considerations of manufacturing technique as the focal length. Although on the one hand the largest possible aperture is desirable, to secure short exposure times even in bad weather, this can lead to lens dimensions difficult to handle in large scale production, as already explained in the discussion of focal length. In addition, it is even theoretically difficult to obtain adequate resolution of detail with a picture size of 30x30 cm., long focus and simultaneously large aperture. Lenses fulfilling such simultaneous requirements would have to be of a focal length between 50 and 75 cm., with an aperture of 1:5 to 1:6, and their production would therefore represent a technical feat of considerable magnitude.

In regard to enemy [i.e., non-German] aerial photography equipment, it must be noted that for many years now, almost no further development has taken place. There is thus an appreciable divergence between the efficiencies of the apparatus used by either side in the war.

Comparison of the efficiencies of aerial cameras proceeds from the picture size, picture angle, and quality of the lens. Reverting to the definitions stated at the beginning of the present paper, the picture size in relation to the picture angle determines the scale, while the picture angle at fixed focal length is a measure of the ground area covered by the picture. In either case, the quality of the lens determines the amount of detail attainable in the picture. The quality of the lens in this context is represented by its resolving power and contrast level. For obvious reasons, such data cannot be given for the German lenses, but it may be stated generally that the lenses used in German aerial cameras are superior to those in enemy [i.e., non-German] apparatus, both in resolving power and in contrast level, and their performance is also better in respect to picture size and picture angle.

It is of interest that this report points out not only requirements on resolving power but also on contrast level. The importance of the effect of the lens itself on contrast of fine detail, quite apart from either target or landscape contrast of gross detail, seems to have been assigned a secondary role in American reports and conferences on aerial photography. It may now be stated, in agreement with the apparently established German view, that resolution and small detail contrast give a dual complexion to the problem of aerial photography. The text below will attempt to discuss these subjects in the light of the still very inadequate available data. It is hoped that before long the uncertainties and numerical estimates will be replaced by more logically determined and controlled test data.

1.2 FACTORS GOVERNING LENS DESIGNS FOR AERIAL PHOTOGRAPHY

Emulsion Considerations. A brief discussion of the properties of the photographic emulsion is presented here because of the light it throws on the overall problem. Let us begin by outlining a desirable experimental procedure of some length based on quantitative and qualitative experiences. Let us suppose that we have an apochromatic microscope objective of extreme quality that forms a 20:1 reduction at a convergence angle in image space equivalent to the convergence of the average aerial camera, approximately $f/6$. Let us prepare a chart of either 3- or 2-line patterns, as the observer may prefer, of sizes descending, by, at most, the sixth root of two. Let the illumination be of sunlight quality, filtered by minus-blue filter as in the average aerial camera, and let us suppose that the illumination produces a surface brightness uniform over the surface of the chart, except for the reflectivity factors of the lines. Let us also incorporate into the chart at least two large photometric areas, one of which agrees exactly with the bright lines, and another with the background. Let us assign an *absolute* surface brightness, and color temperature or its equivalent, to the large brighter photometric area, in order that we may analyze the speed of a lens system in absolute terms. Let us prepare charts covering a range of contrasts, but with only the background varied, and the bright lines held constant.

The image thrown by the designated perfect microscope objective onto the emulsion will therefore be a perfect chart of small dimensions and of dependable, or at least defined, absolute

surface brightness. The microscope is to focus critically on the surface of the emulsion, the criterion being maximum resolution.

An effect that has appeared more than once should be pointed out here for further study. The density or effective speed of the emulsion for the finest resolution patterns appears lower than would be expected on the basis of uniform surface illumination. It is possible that the effect arises from improper laboratory setup, but several high-resolution emulsions have shown a complete disappearance of the bright line pattern before the resolution limit is reached, i.e., a longer exposure would have shown the finer patterns, clearly resolved.

A series of exposures in uniform logarithmic steps are now to be made, with the various contrast targets. A uniform development procedure can be adopted for coarse- and fine-grain development, respectively, in a dual investigation. Development can be as recommended in practice for the several films used, in accordance with any improved procedures.

The end result will be a chart for each type of emulsion in a two-dimensional manifold containing the characteristic curves as derived by microphotometry as a function of resolution, for various contrasts and *absolute* exposure times. This chart can then be considered a complete description of the emulsion as used in aerial photography in heated and dehumidified cameras. It can be supposed with great certainty that a perfect aerial lens at $f/6$ would give identical results. Because of statistical variations in the character of the emulsion, even under well-controlled development, it would be necessary to repeat the experiment enough times to show with certainty that the emulsion has been fairly represented on an absolute basis.

It is, perhaps, unnecessary in this present outline to add experiments on the effect of haze on the emulsion. In so far as the emulsion is concerned, the controlled variation of log exposure and contrast together cover all possible behaviors. In turn, the chart that defines the emulsion becomes an excellent medium for studying the effects of haze in the air. For standard development at constant optimum log absolute exposure of the brighter photometric area (or the density equivalent), one can plot resolution versus contrast as a single curve of fundamental importance for our following considerations. We shall think of such a curve as defining the absolute properties of a "perfect" $f/6$ lens-plus-film combination. See Figure 1.

In a more detailed analysis, the higher color temperature of atmospheric haze would bear close scrutiny. It is evident that, to a close first approximation, haze reduction of contrast can be discussed relative to macroscopic and microscopic detail alike, in terms of the extra density of the darker photometric area, where the total exposure of the brighter photometric area leads to a chosen fixed density on an absolute exposure basis.

Lens-Film Considerations. A lens test according to our outline will now consist of testing aerial lenses in parallel light with a mirror-type collimator with a focal length at least twenty times that of the aerial lens being tested. A complete repetition is made of the photographic test, analogous in every respect to the original emulsion test. Log absolute exposures are again varied in the same steps, with the same targets as used in the first experiment, preferably untouched. A new variable is now added in the form of focal setting for the aerial camera. Because of possible inherent differences in absolute brightness between the original microscope setup and the mirror test, the log exposures of the two tests will be equalized by determinations of the density of the macroscopic bright area on the test charts. Thus, again we have at each part of the field and at each focal setting a chart describing the lens-film behavior. By tying the before and after charts together at equivalent densities of the brighter and large photometric areas, the same coordinate framework can fit both cases and serve as a well-rounded lens test. For simplicity, again the observed resolution can be plotted against log absolute exposure to show film-plus-perfect-lens, and film-plus-imperfect-lens. Note the fundamental character of equivalent surface brightness of macroscopic areas as a means for measuring loss of light from bright lines, caused by poor lens correction. It is our thesis here that the exposure should not favor

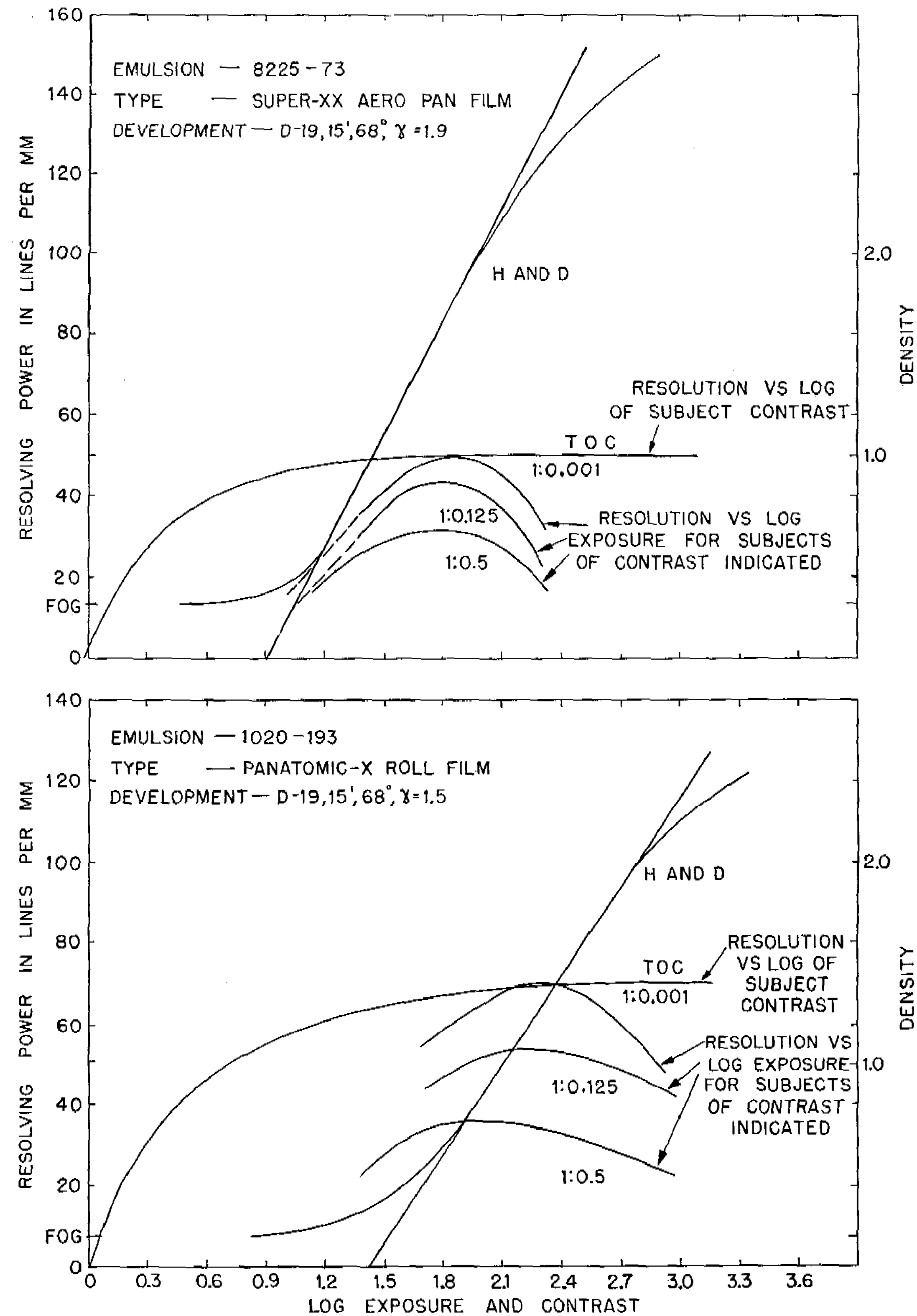

FIGURE 1. Photographic properties of Super-XX and Panatomic-X Aerial film. (Courtesy of Eastman Kodak Company.)

[redacted]

the barely resolved patterns, but should be based only on the photometric areas.

It will be evident that any light lying outside the dimensions of a given resolution line of a given pattern can be regarded as wasted light. The light around and between the lines can be regarded as not only wasteful but as an interference with the results. In so far as the emulsion is concerned, aberration light results in a loss of contrast as a function of resolution in lines per millimeter (what we shall term *microscopic contrast*). Thus, a comparison between the before and after charts of an imperfect lens would show that the loss of microscopic contrast has ended up with a loss of resolution, as defined entirely by the emulsion property at the various altered contrasts. In a target already of low contrast, the lens aberration lowers the microscopic contrast more and more as the limit of resolution is approached, resulting therefore in a still lower resolution reading, but at a progressively slower rate where poorer lens-film performance is shown.

Let us suppose that we have a resolution-contrast curve at optimum absolute exposure for the film-plus-perfect-lens combination. Then, for a film-plus-imperfect-lens test, where the optimum absolute exposure for the brighter photometric area as measured by macroscopic emulsion density has been realized, we will make a reading of resolution obtained. Using this reading, we can obtain a target contrast from the film-plus-perfect-lens curve of the original experiment. Hereinafter, we shall call this final contrast the *microscopic equivalent target contrast*. In a film-plus-imperfect-lens test we can then compare the known target contrast with the observed microscopic equivalent target contrast. Thus, the single reading of resolution by parametric methods will lead to the dual evaluation of resolution and loss of contrast of microscopic detail. Finally, in haze studies, we can speak of *macroscopic equivalent target contrast*. A comparison of macroscopic and microscopic equivalent target contrasts with the actual target ground contrast will present the entire story.

It is believed that lens tests for performance at all field angles should be based on the *one* exposure level that brings the density of the brighter photometric area at a mean field angle to the value found optimum for maximum resolution in the perfect lens-film tests. The density of the same photometric area will then be larger or smaller, in general, at other field angles, leading to a loss of resolution, even in the perfect lens-film combination. The images of the imperfect lens-film combination will cause a further decrease in resolution and microscopic contrast. Vignetting and the cosine fourth law will not only show up readily, but their combined effects on resolution plus lens aberration will then give a truer picture of what the lens will do in the air.

The subject of determining an optimum over-all exposure to favor the performance of an existing lens is, however, a perfectly practical problem and is a phase of the subject that can best be described later under the actual aerial tests conducted. (See Chapter 2.)

Examination of the curves in Figure 1 will bear out the above considerations. On Super-XX aerial emulsion, for optimum exposure (emulsion property) with a perfect lens, a 1/0.001 target contrast yields 50 lines per mm. A 1/0.5 target contrast yields 26 lines per mm. It will be understood that numbers are used here to put the discussion on a specific basis, but that the actual absolute determinations are as yet unavailable. For Panatomic-X aero film, the corresponding figures are 70 and 32 lines per mm. It is evident that Pan-X suffers more from loss of target contrast than Super-XX, although it remains systematically the better film. In turn, if a lens can resolve only 26 lines per mm on Super-XX because of its own contribution to the loss of microscopic contrast due to aberration, the same lens will resolve only 32 lines at most on Pan-X, and probably slightly less, because the effect of aberration on *microscopic* contrast with decreasing line-pattern image size worsens correspondingly.

Note that macroscopic contrast of lens-film must be held constant in these considerations and equivalent to the film tests that precede, and that we are trying to see the final image as the emulsion sees it. Arbitrary adjustment of laboratory exposure time for optimum resolution at each field angle, particularly at high contrast, will lead to test results at variance

with conditions in the air, and is not a measure of performance in a single photograph.

Improvement of the lens design or figuring the aberring system above would show a more marked improvement on Pan-X than on Super-XX at high contrast. Such is the result that might be found in American laboratories with their high-contrast targets. But the aberring lens has reduced the contrast in the imaged target to about 1:0.5 in so far as the emulsion is concerned, that is, the *equivalent target contrast* is 1:0.5, although the known target contrast is 1:0.001.

Let us suppose now that we are repeating the results at low-target contrast, 1:0.5. The perfect lens will yield 26 lines per mm on Super-XX and 32 lines per mm on Pan-X. Now if we expose the imperfect lens so that the macroscopic photometric area corresponding to the brighter line areas reaches the same density (for on-axis image) as obtained with the perfect lens, we find that perhaps one-third of the light has left the effective bright lines and entered or filled up the dark lines between. If we expose to the target of contrast 1/0.5, we find that light leaving the bright lines fills up the dark lines and that a corresponding portion of the dark line illumination enters the bright lines. When this is worked out, we find that the contrast is not far from 1:1. Because the length of the resolution lines is restricted in proportion to the line width, the residual slight difference of contrast is lost in the grain, and the image appears unresolved.

We must remember, however, that this conclusion is based on phenomena in the neighborhood of a resolution of 26 lines per mm on the high-contrast target. The distribution of light in the image becomes less important for grosser patterns at a rather rapid rate. Thus, the test of the imperfect lens on the 1:0.5 target would actually show resolution of the order of 16 lines per mm, which from the emulsion point of view would correspond to an equivalent target contrast ratio of 1:0.74. It is evident that if lens-test curves of the kind described were prepared, one would have the entire story at his finger tips and would be able to discuss what kind and size of aberration to permit in the aberring images (compare Section 1.4.5).

The deterioration of quality in the aerial photograph caused by the imperfect lens is therefore of dual character. There is first a loss of resolution which is more spectacular at high levels of contrast on Pan-X film than at low. Second, there is a loss of contrast in the microscopic image which may not be apparent at all in the macroscopic picture. A microphotometer tracing of the successively smaller patterns will show a steeper rate of decline for the film-plus-imperfect-lens toward the ultimate reduced limit of resolution, even though at macroscopic levels microphotometer tracings of successively finer resolution patterns near the coarse end of the series for film-plus-perfect-lens and film-plus-imperfect-lens can be superimposed. Indeed, the stepping up of the photograph by contrasty development and contrasty printing will serve to recover some of the lost contrast in the microscopic scale but will not recover the resolution. Moreover, tonal values will be destroyed in the process. Macroscopic areas will be too contrasty and unnatural, relative to the partially recovered microscopic tonal values. Contrast loss on macroscopic areas due to haze will be far less than accompanying microscopic losses.

Effect of Haze. Discussion of the behavior of the aerial photograph is still not complete. The aerial haze, which on good days represents a determinable loss of contrast on both macroscopic and microscopic areas, can be analyzed from the point of view of the emulsion. One needs the dimensions of the emulsion chart, log exposure, and resolution versus contrast. For purposes of discussion we may consider that aerial haze plus ground high light (analogous to our previously described brighter photometric area) will lead to a fixed density of the photographed brighter photometric area.

Addition of haze to an aerial photograph represents also a strong variation of contrast with color. Thus, green and red ground targets of identical ground contrast will photograph from the air as a lower green contrast than red. Whether haze, as an integrated function with the net exposure depressed, can be added as a mean value to contrast reduction irrespective of color is debatable. Most probably, the center of gravity of microscopic contrast lies toward

the red resolution versus contrast curves and reacts only sluggishly to green haze losses.

Under these conditions, a perfect lens exposing on ground targets of contrast 1/0.001 in

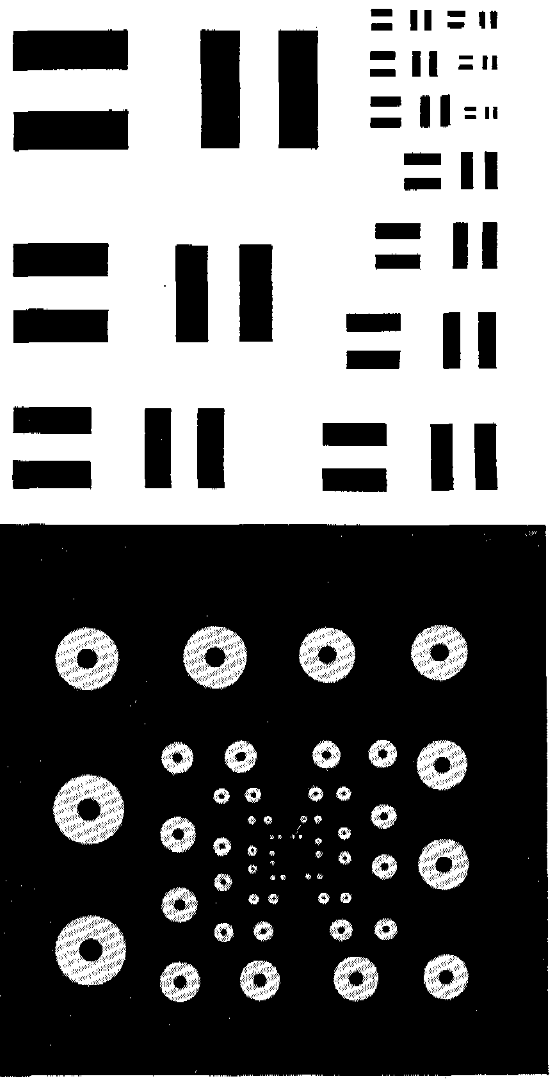

FIGURE 2. The high-contrast Cobb chart and the Canadian annuli.

the American fashion would in the absence of haze attain a resolution on Super-XX of 50 lines per mm and on Pan-X 70 lines per mm. If we consider that haze represents an addition of 50 per cent (common at 30,000 ft) of the high light area to both high and low areas, with haze plus high light constant (and to both macroscopic and microscopic ground detail), we find a loss of contrast to 1/0.33, corresponding to a maximum possible emulsion resolution of 34 lines per mm on Super-XX and 43 lines per mm on Pan-X. An imperfect lens under the same condition as described in the above paragraphs would in the absence of haze resolve 26 lines per mm on Super-XX and 32 lines per mm on Pan-X. With 50 per cent haze added, we find a resultant microscopic or equivalent target contrast of 1/0.60, corresponding to an emulsion resolution of 23 lines per mm on Super-XX and 27 lines per mm on Pan-X.

Carrying through the same thought with respect to the low-contrast targets of the English and Canadians (see Figure 2), we find that the perfect lens, which on the 1/0.5 target in the absence of haze would have resolved 26 lines per mm on Super-XX and 32 lines per mm on Pan-X, now has its equivalent target contrast reduced to 1/0.67, with 20 lines per mm on Super-XX and 23 lines per mm on Pan-X. The imperfect lens, which has in the absence of haze a possible resolution of say 16 lines per mm on Super-XX and 17 lines per mm on Pan-X, now has its equivalent target contrast reduced to 1/0.8, and has a corresponding resolution on Super-XX of 14 lines per mm and on Pan-X of about 14 lines per mm also.

It is evident that in the presence of haze the perfect lens at all contrasts suffers more in proportion than the imperfect lens, but that it remains systematically superior in both resolution and contrast on a microscopic scale. Again, development can recover some of the loss of contrast at a cost of distortion of the tonal values of macroscopic areas. In the presence of vibration, the resultant pictures therefore may not be unsimilar in resolution between the good and not-so-good lens, but the general tone of the perfect lens picture will be better at all levels of brightness than that of the pictures given by the imperfect lens. In other words, even if vibration is found to limit resolution to a fixed value, it would still be worth while to improve the lens design for truer contrast of microscopic detail.

The addition of aerial haze to an already imperfect image therefore produces a much smaller relative change in contrast and resolution than that suffered by the perfect lens. The various phenomena are analogous to the plan-

ing-off effect of a rough board with many bumps of various magnitude down to a common denominator and general level of resolution.

On the toe of the characteristic curve, the situation is much more involved. Resolution has fallen off to a low level because of the emulsion itself. Contrast in the negative is inherently low. Aerial haze over macroscopic areas, as in cloud shadows, will tend to distort the tonal values of the picture even on the straight-line portion of the curve. The difference between perfect and imperfect lenses will become even less noticeable under these conditions, simply because low levels of resolution are involved, and even the poor lens has images of considerably better quality than the emulsion.

On a good photographic day with little haze beyond the inherent scattering of the atmosphere, and particularly at low altitude, pictures made with the perfect lens will take a jump in quality far beyond that obtainable with the imperfect lens.

The situation can be summed up in the following tentative table, where the tabulated resolutions must be taken as representative but not unalterable values.

TABLE 1. Resolution and contrast effects of perfect and imperfect lenses.

Macroscopic ground target	Super-XX lines/mm	Pan-X lines/mm	Ground target contrast	Haze	Equivalent target or microscopic image contrast
High contrast					
Perfect lens	50	70	1/0.001	none	1/0.001
	34	43	1/0.001	50%	1/0.33
Imperfect lens	26	32	1/0.001	none	1/0.50
	23	27	1/0.001	50%	1/0.60
Low contrast					
Perfect lens	26	32	1/0.50	none	1/0.50
	20	23	1/0.50	50%	1/0.67
Imperfect lens	16	17	1/0.50	none	1/0.74
	14	14	1/0.50	50%	1/0.80

These considerations so far are based upon the single comparison of perfect to imperfect image quality. No lens is likely to be perfect over the entire field of view. Many lenses are of extremely high quality over some part of their field of view, but inevitable field curvatures, color aberrations, astigmatism, etc., tend to introduce errors. Most of these errors from the emulsion point of view can be considered a loss of microscopic contrast with correspondingly reduced resolution.

One must remember that the effective loss of contrast, contrary to haze, is a decided function of resolving power itself. It is absolutely necessary to have exact laboratory data before proper discussion of the relationships can be carried through, but such complete data are still lacking. All the above discussions are evidently based on inadequate data. We have neglected log exposure entirely, and have confined ourselves to the best resolution at optimum exposure. In practice, too heavy an exposure at a given contrast will cause an additional loss of resolution, as will too light an exposure. Moreover, the loss of light from the small bright lines of the imperfect image, if we are to maintain the point of view of the emulsion, will mean that for consistent results, equivalent microscopic target contrast should take into account the loss of exposure. Thus, no single resolution versus contrast curve will suffice in a prolonged investigation.

Departures from optimum resolution at any given contrast will in turn join the planing-off process, and tend to affect the good lens more than the bad. If analogy of all effects is made to a mountain, leveling of the peak will proceed quickly at first but thereafter at a rapidly decreasing rate.

Considerations Involved in Lens Designs for Aerial Photography. Considering lens-design, it would seem that for some time to come, while using present emulsions, perfect realization of the Rayleigh limit is not vital nor possibly even desirable. For example, if Super-XX under ideal conditions at 1/0.001 resolves only 50 lines per mm, the single-line width is 0.010 mm. Allowing for some spread in the emulsion, one would suppose that if all the light lay within a circle of 0.006 mm, and had a central peak, the maximum resolution of the emulsion would be essentially realized. At $f/6$, this circle corresponds to about the diameter of the first dark ring of the diffraction pattern, which in turn has a central peak of illumination lying within less than 0.003 mm half-light. Thus, the exact

[redacted]

Rayleigh limit would attain no more than 50 lines per mm on Super-XX at $f/6$, and would have less depth of focus at this peak level of resolution than would a slightly imperfect lens with a 0.006-mm circle of confusion of half-light. In addition, a contrast ratio of 1/0.1 produces an emulsion loss of resolution to only 46 lines per mm for Super-XX and 58 lines per mm for Pan-X at $f/6$, which in turn permits a greater departure from the Rayleigh limit without marked loss of either resolution or contrast, if properly done, and which as a minor correction permits even a slight enlargement of the 0.003-mm core to perhaps 0.004 mm (if the diffraction image with its rings can for turbid emulsion purposes be replaced by a smoothed profile). These figures can all be established on an experimental basis by use of varying amounts of spherical aberration and departure from the Rayleigh limit. It would seem, however, that the emulsion's initially slow loss of resolution with contrast should be used to enlarge tolerances and depth of focus, since no evident loss of quality can be noted in the photograph.

In broad outline it would seem clear that it is desirable to draw rather heavily on the Rayleigh limit, with perhaps only 50 per cent of the light left inside the first dark ring. Such slight imperfection will result in the desired increased depth of focus without loss of contrast or resolution beyond strictly tolerable amounts for highest quality results, and is certainly desirable, if such correction leads to more uniform results over the field of view.

The goal, then, for the optimum aerial lens design, should be to get all images over the field to present the same slight aberring appearance, preferably of residual symmetry such as zonal spherical aberration, overlooking aberration residuals varying at high powers of the aperture, after proper balancing has been accomplished to bring as much peaked light into the 0.004-mm smoothed circle as necessary on a uniform basis.

If we permit aberrations and therefore loss of contrast beyond the tolerances discussed above, it would seem desirable and important that the image retain at all times a central peak with as much light as possible within 0.004 mm and the rest spreading outwards at as high a rate of spread (low-surface brightness) as possible. If the aberration gets larger still, the 0.004 mm will increase in turn to keep pace with the known loss of resolving power of the emulsion at the lowered contrast. This art of balancing should not be overlooked. A factor of 2 in contrast, or 20 per cent in resolution might be the reward for a simpler, well designed instrument of economical manufacture.

If one adjusts an optical instrument visually, by trial and error, it is evident that he should not strive for maximum visual resolution and contrast, which would imply that the peak resolution lies within the Rayleigh limit at a reduced effective aperture, but instead that more zones be brought into the image up to the point where the maximum concentration of light is obtained within the permitted smoothed 0.004-mm circle. Since the effective circle at $f/11$ is about 0.007 mm for complete satisfaction of the Rayleigh limit, another way of looking at the optimum correction for Super-XX is to get an effective $f/11$ entirely within the Rayleigh limit, and for the rest of the light up to the aperture used, say $f/6$, to fill up the 0.007-mm circle and outer rings by departure from the Rayleigh limit, and thereby cause some loss of contrast within that circle.

As the aperture increases from $f/11$ to $f/6$, the original $f/11$ cross section of the image becomes narrowed down into a much smaller central disk at $f/6$ but with a bright first-order ring containing much of the light. Thus, the smoothed profile of the image still approximates the $f/11$ distribution with more total light, but no greater percentage of light in the now more numerous outer rings. The turbidity of the emulsion will soon dissipate the diffraction character of the image into the smoothed profile described above. The total circle of confusion containing all light might be as large as 0.4 mm. The law of decrease of intensity with distance from the core is much more important than the diameter of the circle of confusion.

The poorer image is aided still more by the fact that the faintly outlying halo lies mostly on the toe of the characteristic curve and therefore can be of higher intensity for a mean increase in density for subjects of average bright-

ness. Overexposure with such a lens will find the flare moving up onto the straight-line portion of the characteristic curve and filling up the resolution lines at a rapid rate. An overexposed picture with an inferior lens therefore seems muddy or washed out (low contrast at high density). Underexposure with a poor lens will first of all result in lowered emulsion resolution, but might result in an overall improvement caused by the wings of the aberring image lying entirely on the toe of the characteristic curve. For an inferior lens, there will be, accordingly, an optimum exposure for maximum resolution that differs from the perfect lens-emulsion results. In an aerial picture with such a lens, high lights will therefore appear muddy and low lights underexposed and unresolved. However, a lens designed in accordance with the considerations above will at all levels of contrast and exposure produce a more truly resolved overall picture of relatively undistorted tone values.

The Situation in Practice. These arguments emphasize once more the difference between the British and the American points of view on contrast. The British designer would conclude that he could permit more aberration to the core of the image because the average low-contrast ground images would result in inherently average low emulsion resolution. This, in turn, would permit a growth in the 0.004-mm tolerance to even 0.016 mm without great effect on the net resolution at low contrast 1/0.5. On the other hand, a really good photographic day and good subject contrast would catch such a lens short and result in no great improvement in the pictures.

The American lens designer would adhere to a more rigorous tolerance at the cost of more elaborate and expensive lens designs and production difficulties, without producing any material improvement on average days or targets, but giving full return on good targets and good photographic days, and at low altitudes. Again it should be emphasized that maximum care must be given to ideal balance of aberrations.

Demands for wider angular coverage and faster lens speeds will result in a planing down of future American results toward the more sober level adopted by the British. It is significant that the Germans preferred larger angular coverage to better image quality.

The commercial lenses used in World War II by both British and American reconnaissance squadrons are of comparable quality but fall well below the standards discussed here as basis for further work. Prototype lenses in both countries by a number of companies demonstrate clear improvement in the direction recommended here. With several exceptions, such improved lenses did not reach production in time to be of real value to military photography.

If compromises are made over the field of view, they should be on the basis of area and equalization of departure from the Rayleigh limit. The aberring light will, in general, because of the nature of the assignment, severely crowd the 0.004-mm tolerance on the central core of the image, and in many parts of the field it will greatly exceed the tolerance, because of the nature of the variation of aberrations.

1.2.1 Lens Aberrations and Their Effects on Resolution

Table 2 presents a list of the important aberrations of rotationally symmetrical lens systems as employed in aerial photography. Optical problems are almost always so specialized that no single discussion can present recom-

TABLE 2. Aberrations in the order of importance for resolution and contrast in aerial photography.

Type of error

1. Unsymmetrical errors of the principal rays, independent of aperture, in the general sense, come under the heading of lateral color. There are five chief errors of decreasing importance.
   a. Chromatic difference of magnification, primary spectrum.
   b. Chromatic difference of magnification, secondary spectrum.
   c. Chromatic difference of distortion, primary spectrum.
   d. Chromatic shift of effective stop for corrected pencils.
   e. Chromatic difference of distortion, secondary spectrum.
2. Symmetrical errors of focus, linear with aperture (apart from diffraction considerations).
   a. Error in mean monochromatic focal setting.

[redacted]

TABLE 2—(*Continued*)

b. Astigmatism of all orders (includes curvature of field).
c. Primary longitudinal color.
d. Secondary longitudinal color (secondary spectrum).
e. Variation of astigmatism with color.

3. Unsymmetrical coma-like errors, varying as the square of the aperture.
a. Primary coma (departure from the sine theorem).
b. Oblique coma.
c. Variation of primary coma with color.

4. Symmetrical errors of zones, varying as the cube of the aperture.
a. Primary spherical aberration.
b. Oblique spherical aberration.
c. Chromatic difference of spherical aberration.

5. Unsymmetrical coma-like errors, varying as the fourth power of the aperture.
a. Secondary coma (higher order departure from the sine condition).

6. Symmetrical errors of zones, varying as the fifth power of the aperture.
a. Secondary (zonal) spherical aberration.

7. Residual errors varying with sixth and higher orders of aperture.

Vignetting. Of great importance for aerial photography. This should be considered an aberration and minimized, even at expense of central aperture, with compromise depending on the problem. Includes consideration of cosine fourth law.

Silhouetting. Of importance because of diffraction effects and lowered efficiency, without compensation in depth of focus. Typical of louvre shutters and mirror systems.

Distortion. Importance ranges from vital to no importance, depending on the problem.

Double or Multiple Images. In some lens designs, there exist in off-axis star images separate nuclei of definition, each individually representing a Rayleigh limit or peak of light intensity. Interferometer fringe tests would show two separated areas on the entrance pupil lying within the Rayleigh limit separately, and not necessarily in the same phase, or wave front. The most common case occurs with corrected pencils of skew character, arising from above and below the meridian plane. Out-of-focus photographs suffer particularly.

Flare. Internal reflections that throw fogging light onto the emulsion. Worst case is when ghost image is nearly in focus with true image. Aggravated by many air-glass surfaces. Reduced by surface coatings.

Scattered Light. Light scattered either directly or indirectly onto the emulsion from soiled surfaces or improperly darkened lens edges, cells, or lens barrel. Matter of good design and care of instrument.

Efficiency. Maximum transmission of useful light in proper filter range is desired. Total glass absorption should be considered at time of design. Greatly improved by surface coating that transmits light of proper color.

Centering. Lens centering is a matter for careful workmanship. Aberration caused by poor centering may appear as coma-like flare in center of field, and astigmatism and field curvature in the outer part of the field, varying with orientation around the axis. Analogous to points 2 and 3.

mendations that might cover all cases. However, by having a thorough knowledge of the underlying arguments the reader can always determine for himself what to do for a given problem.

The table lists symmetrical errors in the sense of image symmetry around the chief ray. In general, symmetrical errors are more desirable if measurements are to be performed, and should be at least of the third order if present. Unsymmetrical errors should be of at least the fourth power in the aperture for good results. Departures from the Rayleigh limit as recommended previously will then be in the sense of introducing third-order aberrations to balance the fifth and higher orders as required by the above considerations.

A typical instance is given by what the British term the Ross spherical correction. This consists of overcorrecting the rim rays at $f/6$ (or other comparable maximum aperture) in order to improve the diffraction correction at $f/8$ and particularly $f/11$. This correction results in "clean" images at $f/11$, with the ordinary $f/11$ depth of focus increased by the zonal aberration still within the Rayleigh limit at that aperture, in contrasty but not perfect images at $f/8$, and in good resolution at reduced contrast of the images at $f/6$. At every aperture the new type of correction would be superior photographically in performance and focal tolerance over the ordinary rim-ray correction.

UNSYMMETRICAL ERRORS OF THE PRINCIPAL RAYS, INDEPENDENT OF APERTURE

Lateral Color. The most important aberration in an aerial camera of large coverage is lateral color. At every point in the field the color dispersion laterally around the chief ray should be minimized and kept well within the 0.004-mm circle. No considerations of depth of focus enter, and hence the lateral color should be reduced to the barest minimum. The lateral spread of the principal rays with color is deleterious because the emulsion is almost uniformly illuminated within its own sensitivity curve in cross product with the filter and with the character of the illumination. The aberration is a blurring and outright destruction of

tangential lines, which we speak of as tangential resolution. For best results this aberration, together with the monochromatic aberrations discussed below, demands that the core of the image as a whole be formed within a 0.004-mm circle even to the corner of the picture. There is no question of *should be*. This correction is a *must*.

Since the position of the chief ray is defined not only by the magnification but also by the distortion of third and higher orders, the chief consideration at any field angle is the primary spectrum. It may be necessary to balance residuals in one part of the field of view (chromatic difference of magnification) against the corner (chromatic difference of distortion) error to reduce the net result overall to a satisfactory minimum. Even though this balancing may result in a nearly complete elimination of primary lateral spectrum of the principal ray, there may still remain a secondary spectrum of the principal rays, increasing linearly with field angle (and residually, even as the cube), and therefore worst in the corners. This aberration is serious in many telephoto systems. If not eliminated, at least the minimum or maximum distance of the Gaussian point plotted against wavelength should lie in the effective spectral center of the filter and film combination. For minus-blue filter and Super-XX, this wavelength of best lateral color correction should lie in the neighborhood of sodium light. For color photography the error should be minimized even more to allow for the greater spectral range, and the point of best correction should move into the green. Many lenses that give reduced tangential resolution are actually afflicted with lateral color instead of astigmatism. Since lateral color is independent of stop opening, vignetting that permits retention of some image quality relative to tangential astigmatism is of no help. (See section on *Vignetting*, also in Section 1.2.1.)

It should be noted that lateral color is defined always by the lateral displacement between the best image-forming pencils in respective colors. Thus, the image core may contain a most symmetrical principal ray that defines a stop position for each wavelength. Displacement of the stop with color should be taken into account at each field angle. The problem is simply one of comparing blue-image quality and position with red at each field angle. Lateral color computations should also be referred to the best mean focus over the field, where the film is to lie, rather than to heights in the various optical focal planes displaced longitudinally with color, and in selecting this mean focal plane one should consider zonal errors of aperture and field curvature.

Symmetrical Errors of Focus Linear with Aperture

The second most serious aberration from a resolution point of view for a highly corrected lens system, within the meaning of our earlier discussion, is departure from the best focal setting. Even though departures from the Rayleigh limit are allowed in order to increase focal tolerance without markedly reducing resolution or contrast, in the air focal errors are often ten times or more the desired tolerance. The good lens will have a depth of focus photographically of 0.005 in. on either side of the mean. Focal errors of 0.050 in. have not been uncommon in the past under field conditions, and have averaged probably 0.020 in. With the introduction of thermostated cameras, enclosed in a vacuum or gas-filled, changes of focus can be reduced to 0.005 in. Hence, future improved lens designs might well consider the optimum state of correction and rather restricted depth of focus.

To have the film out of focus is quite deleterious to the definition of near perfect lenses. The out-of-focus image under such circumstances is from the emulsion point of view a uniformly illuminated area, rather than a loss of contrast. Therefore, the emulsion can make no distinction between areas of higher brightness and is obliged to photograph the blurs as such. Thus, a primary rule is that extremely well-corrected aerial lenses inherently have small depth of focus and *must* be in focus in order to give their best performance. Another way of looking at the problem is this: If a lens must be out of focus from uncertainties of one kind or another, it is better that the lens be not too highly corrected, if average results of high quality are to be obtained. Of course, the real answer is to focus cameras critically rather than to relax

[redacted]

the quality of correction any more than is desirable, and to overcome the causes of focal errors in other ways.

The resolution patterns used at present often exhibit a larger depth of focus than would be expected geometrically and physically. Resolution versus focus measured with the originally described "perfect" $f/6$ microscope lens will show this greater-than-expected range. The reason is that the limiting resolution occurs where the dark space between bright lines closes up or, in other words, the bright lines are very much fatter than the dark ones. If plots are made, based on a constant minimum width for the dark line, nearly perfect agreement with observation can be obtained. The apparently large resolution depth of focus in practice is a result of the above effect, diffraction depth of focus, and zonal aberrations. It should be pointed out that fine dark details, like wire shadows, are much more sensitive to focal changes than fine bright details, like railroad rails, in terms of visibility, if not of resolution.

The aberration known as curvature of field is almost identical with departure from focus. This error can be minimized by lens design, although the very nature of lenses precludes flattening the field sufficiently at wide coverages. If the Services were to adopt a curved platen, the designer would seek to obtain his best resolution on a slightly curved surface rather than on a plane. Most generally, the focal surface curves forward toward the lens to a minimum focal setting at a mean zone of the field, and thereafter curves away from the lens system at an increasingly rapid rate. The Services might well adopt a curved platen, where the corner has the same focus as the center, and where intermediate zones are curved forward in a special way by perhaps 1 mm, provided the designers are instructed to fit this focal surface at full aperture as well as possible. Specialized lenses should be fitted still more accurately, preferably with their own magazines, but possibly with aspheric field flatteners.

The linear error known as astigmatism is more deleterious than curvature of field. A curved platen can be made to fit one or the other, or the mean, of the astigmatic focal surfaces, but cannot fit both simultaneously. Therefore, it is up to the designer to minimize the astigmatism at every point of the field to meet as well as possible the requirement that the effective core of light fill a 0.004-mm smoothed circle. Preferably, the astigmatic surfaces should coincide throughout the entire field of view in order to prevent spreading apart of the respective tolerances on depth of focus.

Primary longitudinal color and chromatic difference of astigmatism are approximately identical aberrations and are additive at every part of the field. Pure primary longitudinal color on the axis still produces a peak to the intensity distribution across the image, partly because of diffraction, and partly because the film will be focused accurately for some one color. Colors near the focal setting will be small images; colors near the extremes of the spectral range are out of focus and present uniformly illuminated disks. The image integrated over the spectrum therefore presents a peaked distribution as is desired for maximum retention of resolution and contrast.

Secondary longitudinal color or secondary spectrum also presents a peaked resolution even more sharply defined than that of primary color. The rate of variation of focus with color is not linear but varies as a function of rates of change of dispersions. Therefore, over a wide range of spectrum the axial image, otherwise well corrected, will lie within the Rayleigh limit. Out of focus colors will appear beyond a certain color on either side of the chosen color of best correction. The image in any such color will be of uniform illumination in the absence of other aberrations and diffraction considerations. The integration over the spectrum will produce a sharply peaked image and present some loss of contrast in the image.

Because of the nature of emulsions, the loss of resolution and contrast caused by secondary spectrum is usually rather minor. Unfortunately the aberration cannot be minimized or eliminated with ordinary glass types of lens construction (unless otherwise poorly corrected systems like the Petzval lens are adopted). Improvements can be achieved with fluorite, with certain other crystals, and with a few German glasses. Secondary spectrum is exaggerated in telephoto lenses. This increase, the longer

wavelength range required for color photography, and the fact that the best correction of telephoto aerial cameras is usually in orange light, combine to make present telephotos unsuitable for color photography.

At any given field angle, it is imperative that a lens of optimum performance have all errors which are linear in the aperture and also lateral color reduced to such an extent that the core of a star image lies within a 0.004-mm circle. Aberrations of higher order admit of circles of confusion depending on that order, with proper balance maintained at all times between the ability of the emulsion to resolve at the contrast resulting from the aberration and the diameter of the central peak containing as much light as balanced aberrations will permit.

In view of the approximate addition rule of reciprocals of individual resolutions caused by separate factors, it would appear that tolerances on increased core aberration diameter with lowered resolution due to contrast losses should proceed at perhaps a ratio of one to three. Thus, if the emulsion resolution falls to 25 lines per mm due to the loss of contrast of the aberring image, the core aberration containing as much balanced light as possible should be about 0.007 per mm, with contrast as good as possible within the restriction.

Since errors of astigmatism of various orders are often extremely hard to eliminate, particularly if wide-aperture lenses are needed, it is better to soften the focus along a principal ray to increase the permitted depth of focus at maximum resolution and contrast obtainable than to correct too vigorously for the higher aberrations. It goes without saying that astigmatism should first be minimized.

Unsymmetrical Coma-like Errors Varying as the Square of the Aperture

These errors consist of three aberrations as listed in Table 2. Third-order or primary coma can almost always be eliminated by proper choice of lens data, but in practice, it should have a residual for the purpose of balancing any oblique or secondary coma that may be present. It should be emphasized that the oblique coma referred to under this heading is often just a reappearance of third-order primary coma at large field angles. Consequently, a residual linear variation of primary coma over the field can be balanced against the minimized cubic variation with field angle of oblique coma, resulting in a balancing over the aperture effective at any field angle into the very corner.

If possible, it is well to eliminate oblique coma altogether, since the squared variation is still too exacting on loss of contrast and resolution. In other words, comatic flare is not the best residual aberration for softening up the focus along the chief rays, although it is definitely preferable to linear aberration. The coma should be drawn on only if absolutely necessary. Balancing of coma, as of other aberrations, should be done with the vignetting of the system in mind. If the vignetting is small, it is apparent that the type of balancing will approach a fixed choice of primary coma, and the function of increased vignetting will be to limit the flare and improve the contrast of the off-axis images. But in aerial photography, vignetting should not be drawn on for reduction of aberrations. Rather, the central aperture should be diminished.

It should be pointed out that the oblique coma described here is not the coma of higher order given by the sine theorem. The sine theorem applies only to linear variations of comatic flare with field angle and varies as progressive even powers in the aperture. Oblique coma is more nearly like application of the sine theorem to the principal ray at a large field angle.

There is another type of oblique coma varying as the square of the aperture and the cube of the field angle. The aberration is in the nature of a radial line without vertical height (independent of the skew direction in the aperture). Radially this aberration presents the peaked distribution desired, subject to the discussion of the preceding paragraphs. Tangentially, the aberration is nonexistent or can be considered absorbed into the usual considerations of depth of focus for radial lines.

Symmetrical Errors of Zones Varying as the Cube of the Aperture

Symmetrical errors of zones that vary as the cube of the aperture permit of a softening of

[redacted]

focus in a symmetrical fashion without drastic loss of contrast or microscopic resolution. On axis, the aberration is simply primary spherical aberration that can almost always be eliminated, but which in practice should be used to balance out the fifth and higher order spherical aberration within the meaning of proper balancing for aerial photography. (See discussion of Ross correction at beginning of Section 1.2.1.)

Off axis, the third-order or primary spherical aberration frequently reappears, varying as the square of the field angle, and is called oblique spherical aberration. Oblique spherical aberration actually consists of two separate aberrations, the first of circular distribution analogous to primary spherical aberration, and the second of figure-eight form. Oblique spherical aberration, astigmatism, and curvature of field should be always considered together for maximum depth of focus at every field angle within the desirable tolerance. On the other hand, oblique spherical aberration very often is of large magnitude quite apart from a controlled residual of proper sign for softening of the astigmatic bundle. Indeed, since astigmatism, at least of the third order, is controllable, in practice one more often introduces astigmatism and curvature of field to whatever extent is necessary together with oblique spherical aberration to produce the optimum results in the meridional plane and in the skew direction. Much of the lens designer's time is spent on the oblique spherical aberration and higher order astigmatism problems. Because of the inherent difficulties in satisfying the Petzval sum, any residual oblique spherical aberration should be, and usually is, in the overcorrected direction.

Unsymmetrical Coma-like Errors, Varying as the Fourth Power of the Aperture

Unsymmetrical coma-like errors are rather ugly visually, but fortunately affect the photographic results to an unimportant degree. Primary coma can be drawn on to a limited extent to balance the core of the higher order coma, to the amount considered optimum. The usual observer will exclaim at the large extent of higher order coma and may consider the lens bad, even though improved results have been achieved in the lower order aberrations.

Symmetrical Errors of Zones Varying as the Fifth Power of the Aperture

These errors are commonly considered the limit to the possible speed of a given lens design. To a large extent, useful lenses can be obtained in the presence of large amounts of this aberration, but in practice designers are unable to withstand criticism of axial images having a large flare of low surface brightness surrounding the peak of the image. Many lens designs would profit immensely if the barrel could be shortened for the improvement of astigmatic variations of higher order and for improved flatness of effective field. The usual consequence of a shortened barrel at the expense of increased lens curvatures is large fifth-order aberration (which is identical with zonal aberration, after proper third-order balancing has been achieved).

Residual Errors Varying as the Sixth and Higher Powers of the Aperture

By now it is clear how aberrations affect the image quality photographically. Aberrations of sixth and higher order may present large circles of confusion and some loss of contrast but have no very serious effect on resolution. These aberrations are most usually controlled by adapting the aperture to the type of design. The lens designer becomes somewhat of a painter, hardening the focus at one point and softening it at another. The process would be of considerably greater interest if automatic computing machines could be used to take the drudgery out of the numerous routine computations involved. Often, even a minor variation requires recomputation of an entire bundle of rays through a system. The Army and Navy might well consider that their sponsorship of automatic methods would be of material importance to the ultimate improvement of their apparatus, even though at present it may seem like an unassociated development.

Vignetting

The effect of vignetting is first of all to cause undesirable variations in negative densities and thereby to make procurement of good prints a more difficult matter. More important still, the

optimum exposure on axis adjusted for maximum resolution on the emulsion may mean that in the corner the illumination is down on the toe of the characteristic curve, with resultant loss in resolution and contrast. Dodging of prints to recover some density and contrast in the corners distorts the overall tonal values and, of course, cannot recover resolution not already in the negative. The wisest course is for the designer of aerial lenses to consider vignetting as an aberration and to equalize the exposure over the picture size by sacrificing some attractive but relatively unimportant central definition.

In average military practice, in the presence of uncertain lighting conditions and rule-of-thumb methods, it has proved necessary to adopt an average overexposure in order to prevent complete loss of numerous underexposed pictures. Lenses with little vignetting would tend to reduce such losses since lighter pictures might be used. It is hoped that future developments in automatic iris control, or preferably in shutter-speed control, will reduce the uncertainties and permit an average optimum exposure. If overexposure is necessary, however, it is evident from all the preceding discussions that the good lens design with "clean" images will give much sharper and more contrasty dense negatives than will poorer lenses with reduced resolution and "muddy" images. The common practice of developing aerial film to a high gamma is both unnecessary and undesirable for photographs made with a really good lens. The proper gamma should be primarily for compensating whatever haze was present at time of exposure, plus a bit more to allow for accumulated effects of residual aberrations and for scattered light. Tonal values in areas of under-illumination will inevitably still be distorted, but at least the best possible results will have been obtained. If the negative is exposed longer to bring up areas of low illumination, the overexposed high lights will tend to retain their proper contrast and the maximum resolution permitted by the emulsion at the density involved.

Distortion

Reconnaissance with long-focus cameras seems to permit rather considerable distortion without marked effect. Only when mosaics are pieced together or when photographs are used for mapping purposes will distortion be of real importance. The subject is so familiar that discussion can be minimized here. From the lens point of view, it is possible in many types of symmetrical designs to keep the distortion at exceedingly small values, measured in microns of displacement. The designer should base his judgment on proper balance of all requirements of the problem assigned.

Discussion

Considerations of large-scale high-quality photographs demand that quality be considered by area rather than by a high peak on axis and progressive deterioration radially to the corner. Designers would be much freer in their judgment if government laboratories would appreciate the points involved and would formulate their specifications accordingly. The practice of the British, the Canadians, and the Eastman Kodak Company workers in weighing the performance of lenses by area or "number of resolvable units" should be adopted in equivalent form by everyone.

It would be fair to the designer if the picture size to be covered could be definitely specified. For example, requests are often received to design for only the included circle in the square picture frame. It would obviously be unfair for corner areas to be included in final tests of such lenses. Designers themselves should also be forewarned that problems of limited scope almost always grow into more rigorous requirements in the end. A designer who does design for the included circle or restricted aperture will almost always find his lens replaced by some lens of equal performance over a large area or of higher speed, and even by lenses of lower quality with good corners or somewhat higher speed.

It is important to consider the problems and requirements of the Services carefully for maximum economy, production, and early delivery. A doubling of tolerances on distortion, or a slightly reduced aperture, might permit a very great increase in production ease and economy. It is significant that many German designers try to obtain the utmost from rather simple combinations. The Zeiss Telikon telephoto and

the Topogon are good examples of thrift in lens design.

1.3 LENSES AND ASSOCIATED EQUIPMENT

The great complexity and variety of the problems encountered in the course of World War II prohibit the writing of a completely coherent account of the developments in lens design throughout the United States and in other countries. It seems best to confine ourselves to group classifications of equipment, and then to proceed on the basis of individual topics.

1.3.1 Lenses Developed for Day Photography

WIDE-ANGLE PHOTOGRAPHY (HARVARD)

Contract OEMsr-474 with Harvard University was entered into on May 1, 1942. Up to that point Harvard had started an optical shop for the construction of several types of aerial lenses under purchase orders with the Photographic Laboratory at Wright Field. One of these lenses with associated equipment comprised a system for wide-angle photography[3] that appears to be of promise and might be useful when developed to a practical state. NDRC undertook to carry on the wide-angle work in September 1942, even though more important items were given precedence in order of urgency and utility.

The lens design selected for the Harvard wide-angle system was similar to the spherically symmetrical scheme proposed by T. Sutton in 1859, but was brought to a high state of perfection. In the final form adopted, the lens consisted of a spherical crown lens with central stop and filter, cemented within a spherical shell of flint glass, also with a completely spherical outer surface. The choice of glass types and radii combined to produce a well-corrected image over the entire sphere at speeds of $f/2.8$ and $f/3.5$, according to the model.

Selection of a spherically symmetrical lens system introduced many practical problems. The field of best definition was spherical and concentric with the lens elements. In order to photograph over angular fields as large as 120 degrees total coverage, it proved necessary to resort to emulsion-coated glass shells of special manufacture.

In conjunction with the picture-taking lens, it proved necessary to design and construct a projection lens capable of projecting the spherically curved negative onto an enlarged, flat, undistorted print. Up to the time NDRC became responsible for continuation of the program, Harvard had delivered to the Air Corps one complete system, comprising taking lenses of 4-in. focal length at $f/2.8$ (there were two separate lens systems, one with red and one

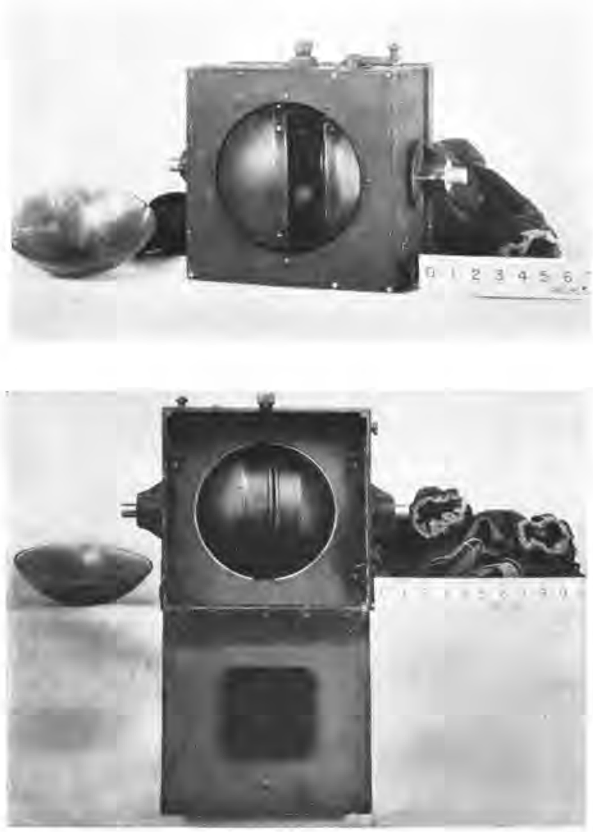

FIGURE 3. Front and rear views of wide-angle camera with $f/2.8$ spherical lens.

with infrared filters cemented between the central hemispherical elements), a camera with rotating ball shutter, a projection lens enlarging to 40x40 print size, and an enlarging cabinet for housing a fluorescent illuminator and the projection lens.

Figures 3 and 4 show views of the pre-NDRC apparatus. It is to be noted that the camera

shutter started from rest each time, swept with a narrow slit across the emulsion, and came to rest against a shock absorber after traveling through a 180-degree arc. A shutter speed of

FIGURE 4. Projector for use with 120-degree wide-angle camera.

$\frac{1}{300}$ sec was obtained with an efficiency of 90 per cent. Figure 5 shows a cross-sectional view of the projection lens.

Further NDRC developmental work culminated before the end of the war in an $f/3.5$ wide-angle lens of 5.950-in. focal length (see Figure 6). Much work was accomplished on a double ball with differential gearing, shutter, and camera arrangement to provide continuous operation and constant shutter speed over the 120-degree adopted field. Figure 7 shows the scheme of the proposed prototype. Between successive phases of the differential rotation, a slow-moving mechanical shutter operated electromagnetically against spring action through a commutator, was to serve as the capping shutter. The electric relay system was designed to prevent multiple exposures on the same shell from whatever cause.

Although automatic reloading was contemplated at length, no progress was actually made, partly owing to the low priority of the wide-angle program and partly to the inherent difficulties.

As a result of discussion of this development with a number of Army officers, and experience gained over several years of thought on the problem, this system for wide-angle photography may be reduced to the following conclusions.

Conclusions. The performance of a spherically symmetrical lens at $f/3.5$ is nearly constant over any assigned field of view, which for practical purposes may be chosen to be 120 degrees. It is probable that a projection lens can be designed to convert shell negatives into single flat undistorted prints with enlargement $1.5\times$, without great loss of resolution.

Owing to the very high lens-film resolution (70 lines per mm on Super-XX) of this type of lens system at all contrasts, and to the possibility of using fine-grain films at $f/3.5$ with a shutter of high efficiency, most probable aerial resolution of fully-developed equipment is 30 or more lines per mm over the entire field of view. Projection of the negative will produce much lower linear resolution in the outermost parts of the print, relative to the central linear

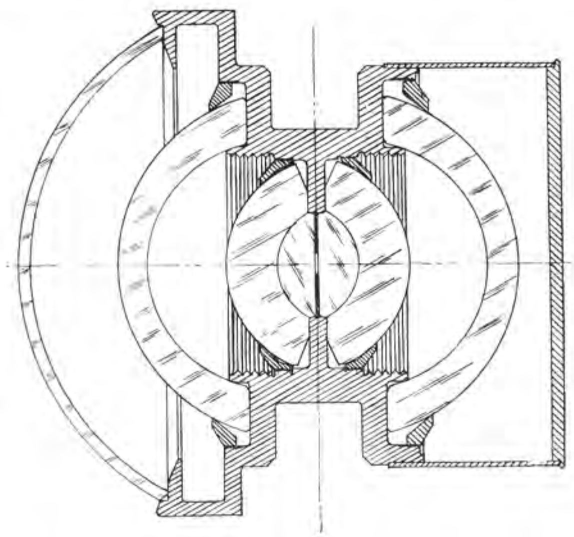

FIGURE 5. Projection lens for curved negatives.

definition, if fair comparison is to be made with standard wide-angle equipment. Because of the constant density of shell negative and of

the practical projection of such negatives, it is certain that the final prints will constitute a marked improvement over those made with flat

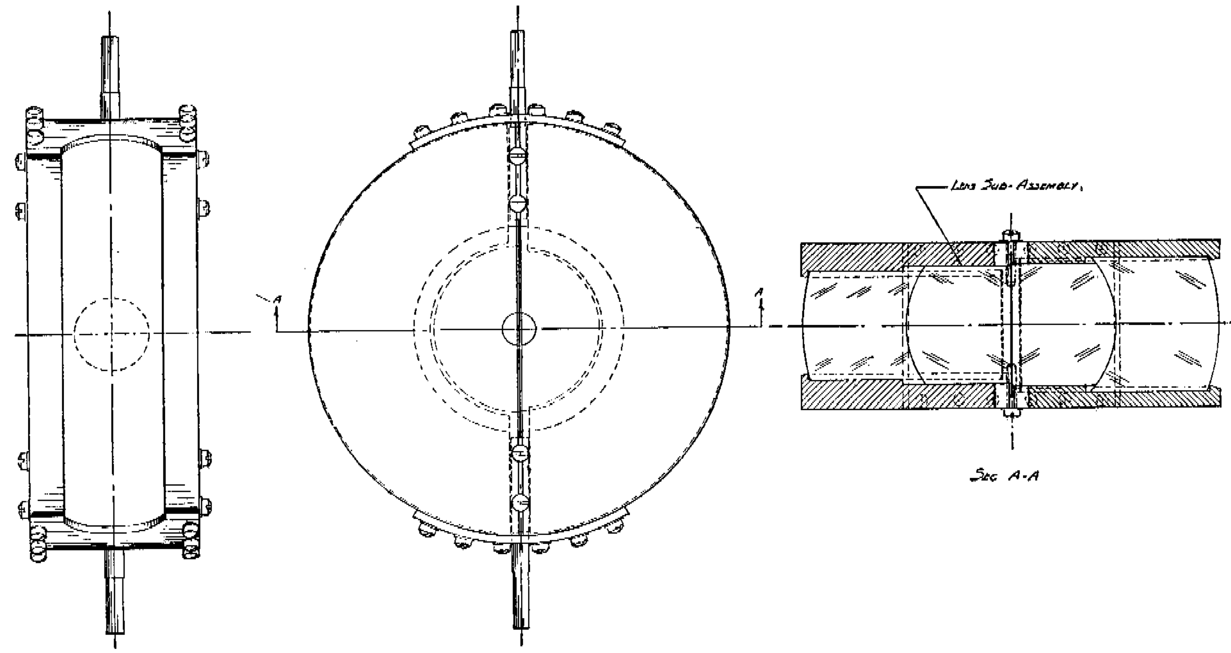

FIGURE 6. The 5.950-in. $f/3.5$ wide-angle lens in cell.

field lenses of comparable speed, and certainly over those of comparable coverage.

The outstanding problem raised by the proposed wide-angle method is lack of convenience. On the other hand, the procedure is best fitted to one or a few exposures permitted over a large area under battle conditions.

The wide-angle devices introduced by Harvard should be re-examined and developed into a practical working unit for 120-degree coverage and intended for a limited number of exposures per flight. Special attention should be given to the convenience and safety of the operator. It is believed that use of the camera from a completely darkened photographic compartment in the airplane would lead to convenience and ease of handling when in the air.

Table 3 lists the equipment for wide-angle photography developed primarily for the Army Air Forces.

Testing. In the summer and fall of 1942, aerial tests were carried out on items 1, 3, and 4, followed by laboratory printing making use of items 5 and 6. The tests showed promise but were not in themselves successful, owing to various difficulties encountered with the airplane and equipment. The use of infrared emulsion was attended with the difficulties of heavy background fog and storage problems. Several shell negatives were made from altitudes of 2,500, 20,000, and 30,000 ft. None was in sufficiently good focus to be spectacular for quality,

TABLE 3. Equipment for wide-angle photography.

Pre-NDRC
1. 4-in. $f/2.8$ wide-angle taking lens with infrared filter.
2. 4-in. $f/2.86$ wide-angle taking lens with red filter.
3. A complete camera with changing bag.
4. One dozen glass photographic shells.
5. One projection lens for wide-angle printing.
6. Enlarger cabinet and fluorescent illuminator.
Under NDRC
7. 5.950-in. $f/3.5$ wide-angle taking lens with red filter.
8. Wide-angle camera, unfinished.
9. Seventy-two glass shells of large size for lens in item 7.
10. Improvements in equipment of items 2, 3, and 5.

but they were striking for their covering power.

Improvements made in the equipment in 1944 and 1945 under NDRC were never tested in the air, although plans to that effect were in prog-

[redacted]

ress. Among these improvements were remachining of the camera, substitution of item 2 in a more suitable cell, and more careful focusing. Ground exposures of panoramic character gave extremely sharp pictures and confirmed expectations.

Prints made in the laboratory in 1942 were striking for their size and coverage, but unfortunately there was lack of sharpness in the negative due to the inadequacy of focus. It appeared from the laboratory printing that the projection lens itself was of suitable quality, but that the enlarging equipment was too cumbersome and needed redesign along more practical lines.

Item 7 was completed in April 1945, and delivered to the Mount Wilson Observatory for testing which made use of the Mount Wilson-NDRC optical bench, and which was conducted both visually and photographically at a number of contrasts. Further tests were conducted at the Eastman Kodak Company in the fall of 1945.

Mount Wilson Findings.[4] (1) The best focal setting with wavelength from 5,800 A to 7,200 A lies in a range of 0.04 mm, with minimum focus at 6,600 A. (2) All errors of asymmetry, coma, lateral color, and distortion were found to be negligibly small, indicating good workmanship. The focal surface was found to be spherically concentric with the lens surfaces within the measuring accuracy of 0.01 mm. (3) Astigmatism was found to be absent, although a slight difference in resolution in tangential and radial directions existed, owing to obliquity of the aperture and loss of diffraction resolution far off axis. (4) Spherical aberration at $f/3.5$ was found to be negligibly small.

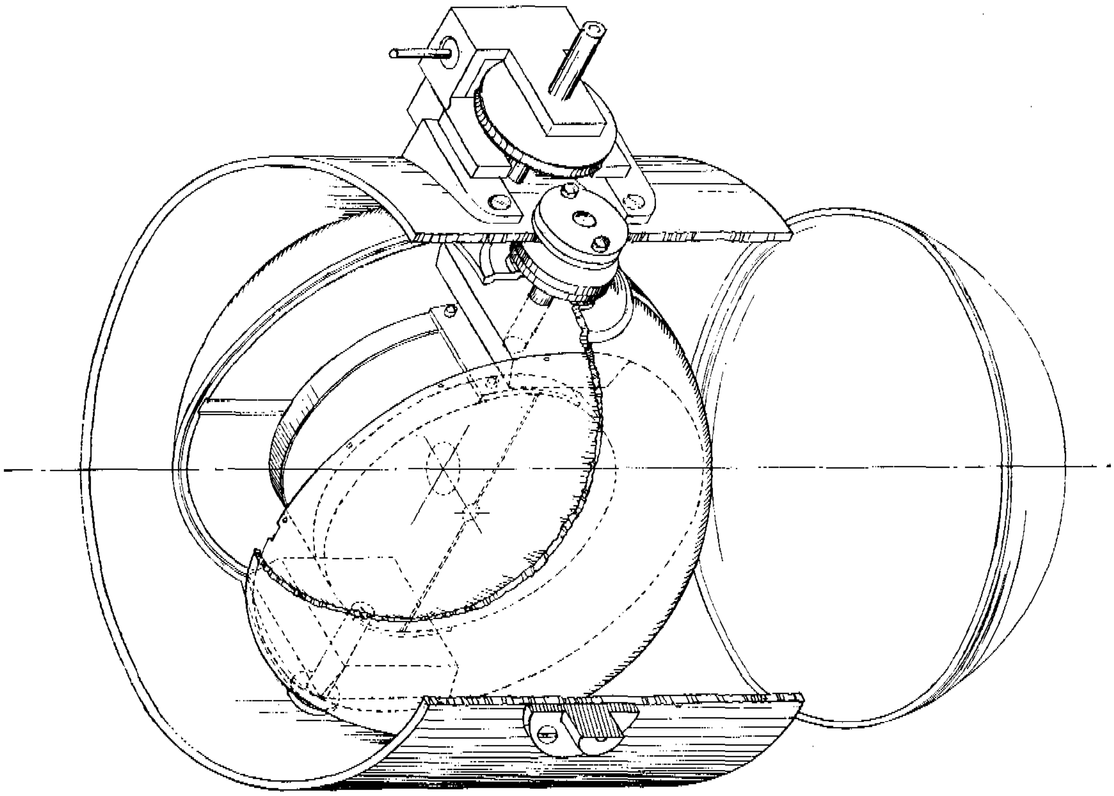

FIGURE 7. A schematic view of the double-ball wide-angle camera.

Resolving power was measured visually and photographically. All photographic resolving powers were found to be higher than 90 per cent of the reciprocal sum of the reciprocals of the resolving power of the lens visually and of the film alone. Maximum visual resolution at 1/0.005 contrast was found to be 400 lines per mm with little scattered light around the image.

[redacted]

Radial resolutions held to this value over the required total field of 120 degrees, but tangential resolution, in agreement with computation, due

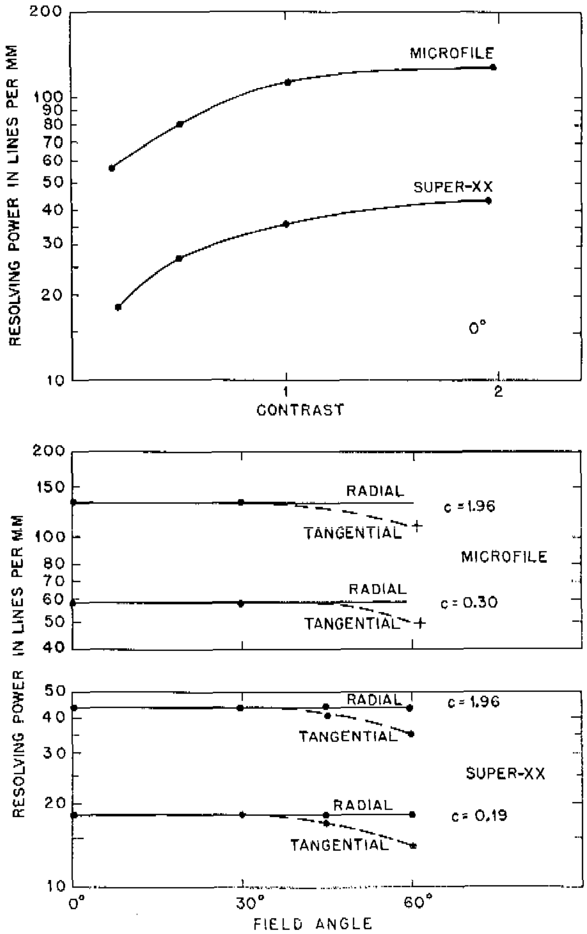

FIGURE 8. Resolution tests on the 5.950-in. $f/3.5$ wide-angle lens.

to the reduced elliptical aperture fell by a cosine law to approximately 200 lines per mm at 60 degrees off axis. Other visual measures at a contrast of 1/0.5 showed nearly constant radial resolution of 300 lines per mm over the field, and tangential resolution falling to 180 lines per mm at 60 degrees off axis.

Figure 8 shows the Mount Wilson photographic results, where the contrast c refers to the logarithm of the ratio of surface brightness of the test target. Figure 9 shows the dependence of resolving power on focal setting at contrast of 1/0.5 for Microfile and 1/0.65 for Super-XX. The curves showing resolution versus focal setting are in excellent agreement with the assumption of constant turbidity of the emulsion, but are in complete disagreement with the assumption that the law of reciprocals holds. Therefore, the comparatively great depth of focus indicated does not mean in this case that the lens suffers from zonal aberration but that the resolved coarser patterns out of focus consist of fat, exposed lines separated by thin, unexposed spaces of the emulsion.

THE 40-IN., $f/5$, 9x9 DISTORTIONLESS TELEPHOTO LENS (HARVARD)[5]

In 1942 Harvard delivered to the Army Air Corps an $f/5$ telephoto lens of 40 in. focal length for the K-22 camera. During 1941 and part of 1942, under direct purchase orders with the Army Air Corps, there had been designed and developed three telephoto lenses of similar character. The first of these was the $f/5$ lens corrected for a minus-blue filter, mounted in an aluminum cone that fitted the experimental K-22 camera, also just delivered to the Air

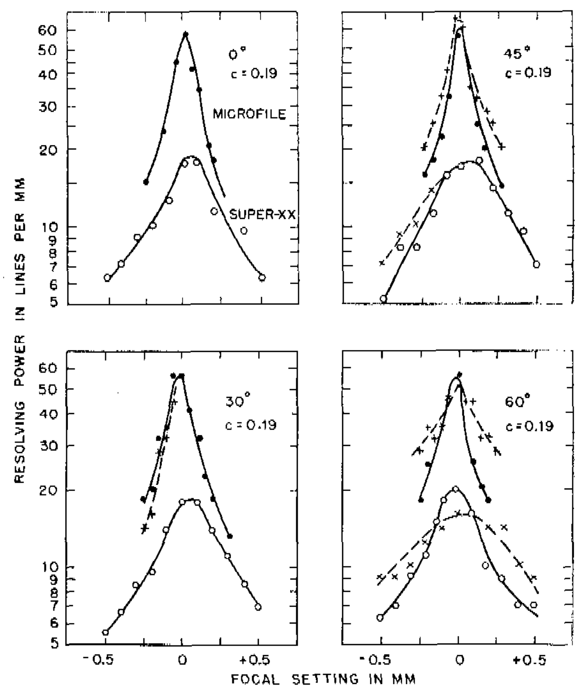

FIGURE 9. Dependence of resolving power on focal setting at low contrast.

Corps by the Fairchild Camera and Instrument Corporation.

The second telephoto, partially completed by Harvard at the time of the NDRC contract,

[redacted]

was a 40-in. $f/5$ for 9x9 picture size, but redesigned for best color correction with an infrared filter. The third telephoto was a 60-in. $f/6$ for 9x9 picture size. The optical parts for this lens were completed by Harvard prior to the NDRC contract, but delivery was held up for lack of a mounting.

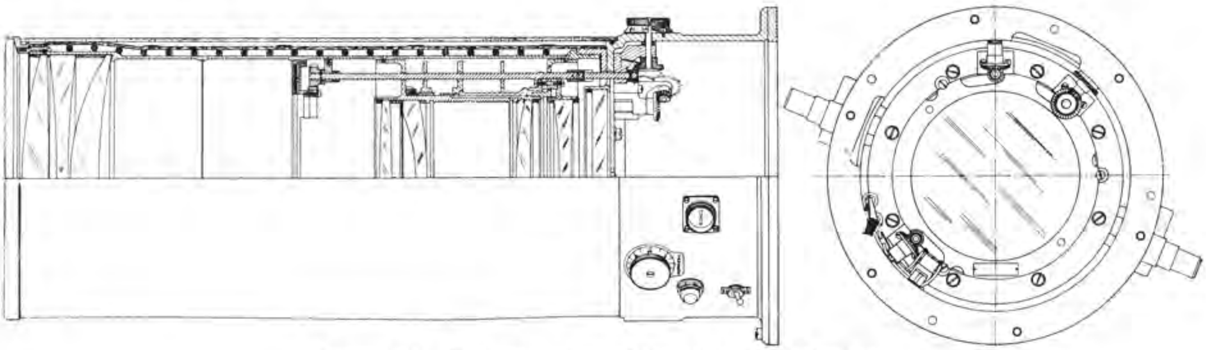

FIGURE 10. Cutaway view of the 40-in. $f/5$ telephoto.

Improvements and completion of advanced models were placed on the new NDRC program as of the highest urgency. In addition, aerial testing carried on at Wright Field in September 1942, and again in February 1943, established that in spite of a 40-in. focal length the $f/5$ telephoto with minus-blue filter was capable of yielding aerial pictures of very sharp linear resolution.

Aerial tests also established clearly that the aluminum mounted telephoto was subject to changes of focus in the air due to thermal gradients and great range of temperature, and to ground-distance and air-density changes with altitude. The efforts of the laboratory at Harvard were concentrated during 1943 and 1944 on means for making the camera system completely compensated for focal changes from any cause.

Production contracts were concluded in May 1943, between the Air Forces and the Perkin-Elmer Corporation, for 100 units of the 40-in. $f/5$ telephoto lens. A contract for 12 units was also made with Harvard. Because of the expected long wait for production of the requisite optical glass, time was taken in the Harvard laboratory to undertake construction of three more experimental telephotos, each of successively greater improvement.

Final Model. The final production model of the $f/5$ 40-in. telephoto with minus-blue filter is shown in the assembly drawing of Figure 10, and the first prototype in Figure 11. It is to be noted that seven elements were found to be necessary to achieve the necessary optical corrections at $f/5$, including the correction of distortion. If distortion had been left badly uncorrected, fewer elements would have sufficed. The filter was located in the converging beam behind the rear element, and the corresponding small optical effects at $f/5$ were taken into account in the lens formula.

The $f/5$ optical system and mounting were

FIGURE 11. The 40-in. $f/5$ telephoto for 9x9.

well integrated into a unit fully compensated to prevent focal shifts. The mounting contains many points of engineering that contribute to production ease, production control, economy of manufacture, and to performance in the air.

One of the novel features of the system is the

unit for automatic focusing with altitude. Calculations had shown the probable change of focus with altitude to amount to many times the detectable depth of focus in the air with the 40-in. lens. It seemed worth while to attempt elimination of this variation in focus in order to provide automatic use of the unattended telephoto in fighter aircraft. The optical construction of the $f/5$ telephoto was well adapted to accomplishing differential focal shifts by means of longitudinal movements of the rear element. Extended computations proved that the aberrations of the system were insensitive to the location of the rear element, out of proportion to the effect of its movement on the focal position. After some careful considerations and experiments the automatic focusing unit shown in Figure 12, which maintains a constant focal plane by moving the rear element, was designed and constructed.

FIGURE 12. The automatic focusing unit and inner cell assembly. (Courtesy of Perkin-Elmer Corporation.)

The change of focus with altitude comprises two effects, one of ground distance from the camera and the other air-density changes. Both of these are additive and together produce the curves shown in Figure 13. In order to eliminate this type of variation with focus as effectively as possible, it was decided to fit the curve with two straight lines, each representing a constant spring rate of a sylphon bellows arrangement. The rear element is suspended in effect between ten springs and ten bellows. At altitudes up to 15,000 ft, six nitrogen-filled bellows under pressure push against the springs and four others, partially evacuated, retard this action. At 15,000 ft, the four partially evacuated bellows move free of the suspension against a stop and are thereafter inoperative. Therefore, above 15,000 ft the spring rate is materially reduced for the system, resulting in a much slower compensation with pressure. Figure 14 shows how well the system so designed and applied worked in practice. In view of the long industrial experience with bellows, there seems to be little likelihood of failure in use from ordinary causes.

Figure 15 shows the results of cold-chamber tests made in 1943 on an early unthermostated model. The thermal gradient caused the focus to shorten in spite of the shrinking of the steel lens barrel, which in the equilibrium state predominates. Note that between the third and fifth hours, the focus moved rapidly away from the lens.

The 40-in. $f/5$ lens was thermostated by means of soil-heater cable wound in two parallel circuits about the camera in such a way that all solenoid effects were eliminated. The heating system was capable of delivering about 100 w at 24 v. To conserve heat and to reduce thermal gradients, the outside of the camera was insulated with asbestos and Micarta tubing. The latter served to protect the camera against shock and handling, and to provide a streamline exterior. Figure 16 shows further cold-chamber tests with a thermostated unit.

Although most commercial aerial lenses, both in the United States and abroad, were mounted in brass or aluminum for ease of production, freedom from corrosion, and in the case of aluminum, for lightness, the production Harvard 40-in. $f/5$ lens, like the German Telikon, was mounted in rustproof steel. It was felt that the long time-stability of steel, its resistance to rough treatment, and its close mating with glass on thermal expansion were highly desirable for a lens system of high precision. The

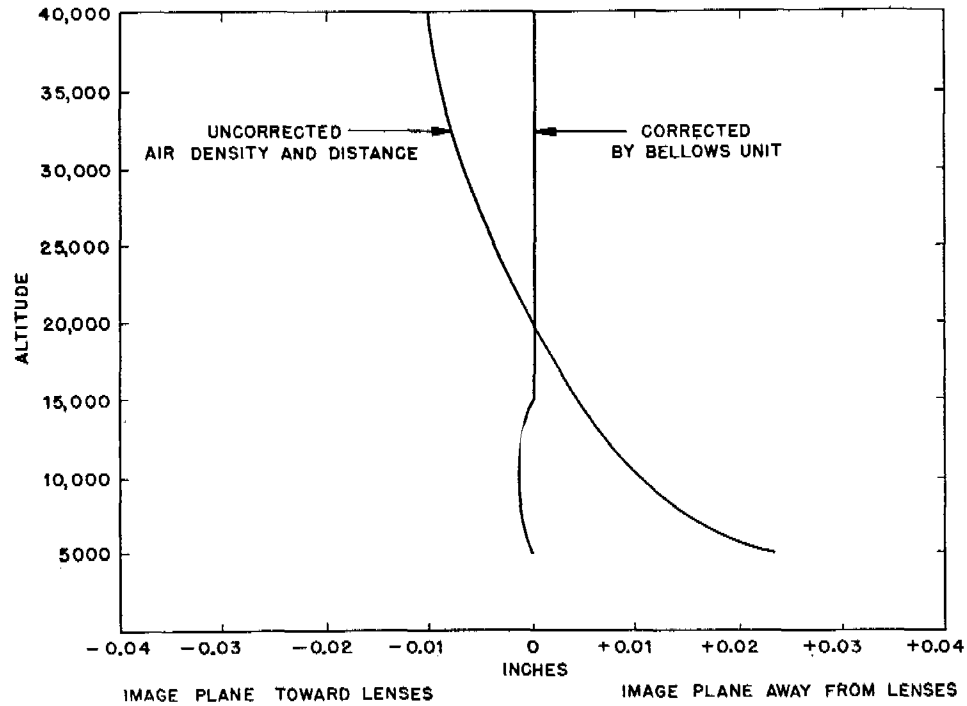

FIGURE 13. Dependence of focus on air density and ground distance, before and after compensation.

use of steel, however, added very materially to the cost of the unit and multiplied the difficulties of mass production.

In spite of the high specific gravity of steel, careful engineering of parts reduced the weight of the complete telephoto system to a reasonable figure. The completed lens system, apart from camera body and magazine, weighed approximately 88 lb. For maintenance of shape with age, all steel parts were subjected to deep freezing before final machining.

The spacer rings shown in the cells for the last four elements were used in production for control of image quality of the system. Differential correction formulas were used that took into account random variations in melts of glass and lens thicknesses. Optical tolerances on radius variation were held to such a minimum, without marked increase in production diffi-

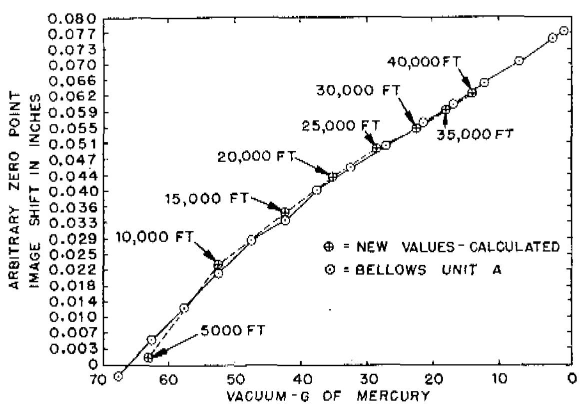

FIGURE 14. Observed and calculated bellows movement.

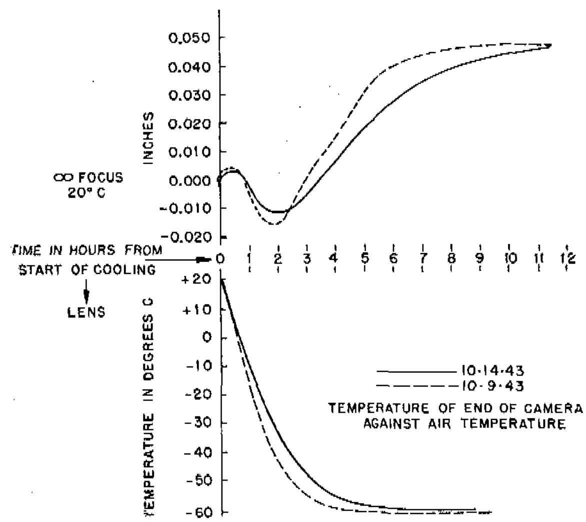

FIGURE 15. Cold-chamber observations with a steel barrel telephoto.

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culty, that all radii were considered to be constant. Indices of refraction were measured by the Perkin-Elmer Corporation on a five-place refractometer. To facilitate such work, each glass blank as delivered contained a boss that could be sliced off, one face polished, and the

B-29's for use in the Pacific area. No reports have been received concerning the lens units in service.

Of the several telephoto lenses submitted as prototypes, only the 40-in. $f/5$ with minus-blue filter was produced. The infrared 40-in. $f/5$

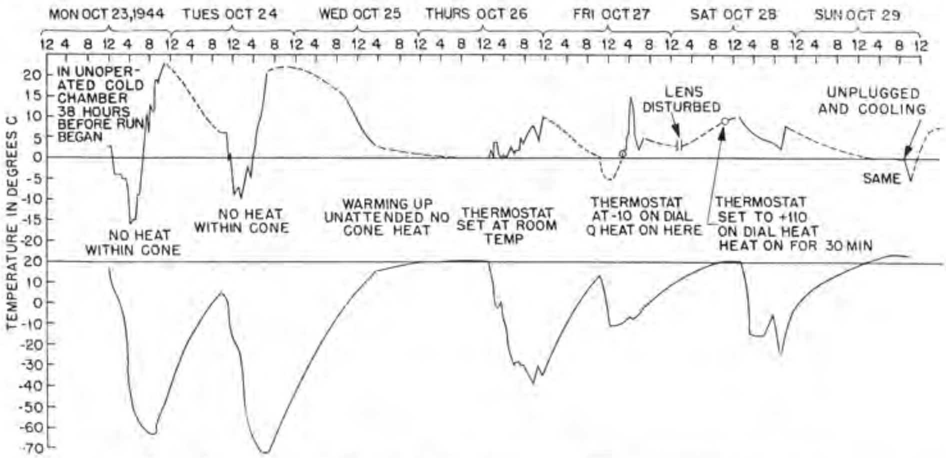

FIGURE 16. Cold-chamber observations on thermostated telephoto.

index of refraction measured. The extra operations proved to be very economical from the point of view of assembly. By means of the differential correction formulas and production control, the later production units rarely had to be disassembled for readjustment.

Production Results. During the period of development of the lens, several other test flights were made at altitudes up to 30,000 ft. The clear pictures made time after time convinced the Air Forces of the utility of the lens in spite of its inherent complexity. Throughout 1944 and 1945 there was constant pressure exerted to get the units into production. Delivery actually began in the spring of 1945. By the end of World War II in August, the Perkin-Elmer Corporation had reached the unexpected rate of 30 units a month. It was quite possible, had the emergency continued, that a production rate of 100 units a month could have been reached. The requirements for this rate, as expressed by the Air Forces, took form in a new contract for another 200 units, and near the end of World War II discussions were being held on procurement of at least 200 more units during 1946.

Installation of the 40-in. $f/5$ was made in

telephoto, delivered in the winter of 1943, was tested successfully, but was never contemplated for production.[5a] A 60-in. $f/6$ telephoto[5b] was delivered in the winter of 1943-44 also. The 60-in. was mounted in a U-shaped camera (see Figure 17) measuring only 16x26x31½ inches, small enough to be used in the nose of a P-38 plane. Aerial tests of this lens during

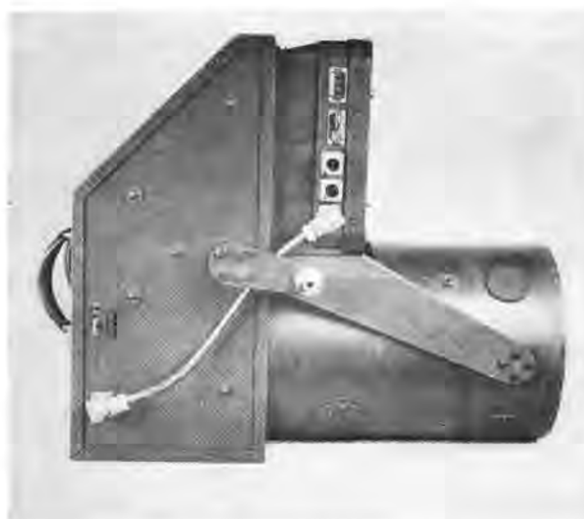

FIGURE 17. The 60-in. $f/6$ U-shaped telephoto.

August 1944 over Dayton, Ohio, proved successful. The lens was later flown over Berlin at least once.

During the fall of 1944, steps were taken to procure one dozen units of the 60-in. $f/6$ for 9x9. Since the design of the optical system was unsuitable for mass production, Harvard provided a reworked design during March and April, 1945. Subsequently, the entire project was canceled, owing to cost difficulties in part, and to the restricted ground coverage.

THE 60-IN., $f/5$, 9x18 TELEPHOTO LENS (HARVARD)[5c]

The lessons gained from the several years of experience on telephoto systems led Harvard to propose a 60-in., $f/5$, 9x18 camera. Although, in principle, this lens was a scaling up of the earlier design, new computations were made for the purpose of improving the vignetting of the earlier system. In addition it was proposed to mount the lens system in a vacuum to combat the rigors of service conditions. Figure 18 shows the proposed system. The end of World War II prevented completion of the two prototype units under way.

The optical system was to be mounted in an internal tube supported in such a way as to minimize flexure with the weight distribution as planned. By use of the principle of a ball inside of a cylinder at the front end, it would be quite difficult for external distorting forces to be imparted to the sensitive end of the system. The ring and outside contact cylinder were both to be sufficiently heavy to withstand any possible blow that might still be transmitted through the thick external rubber cushion. It was felt that the elastic limit of the steel mounting tube could never be exceeded by ordinary forces, short of outright destruction.

The front of the telephoto system was to be enclosed by a heavy plane-parallel window of BSC-2 glass. The rear of the system was to be formed by the rear element itself, purposely thickened to withstand the atmospheric pressure. The filter, again mounted in the converging beam for interchangeability, lay outside the vacuum.

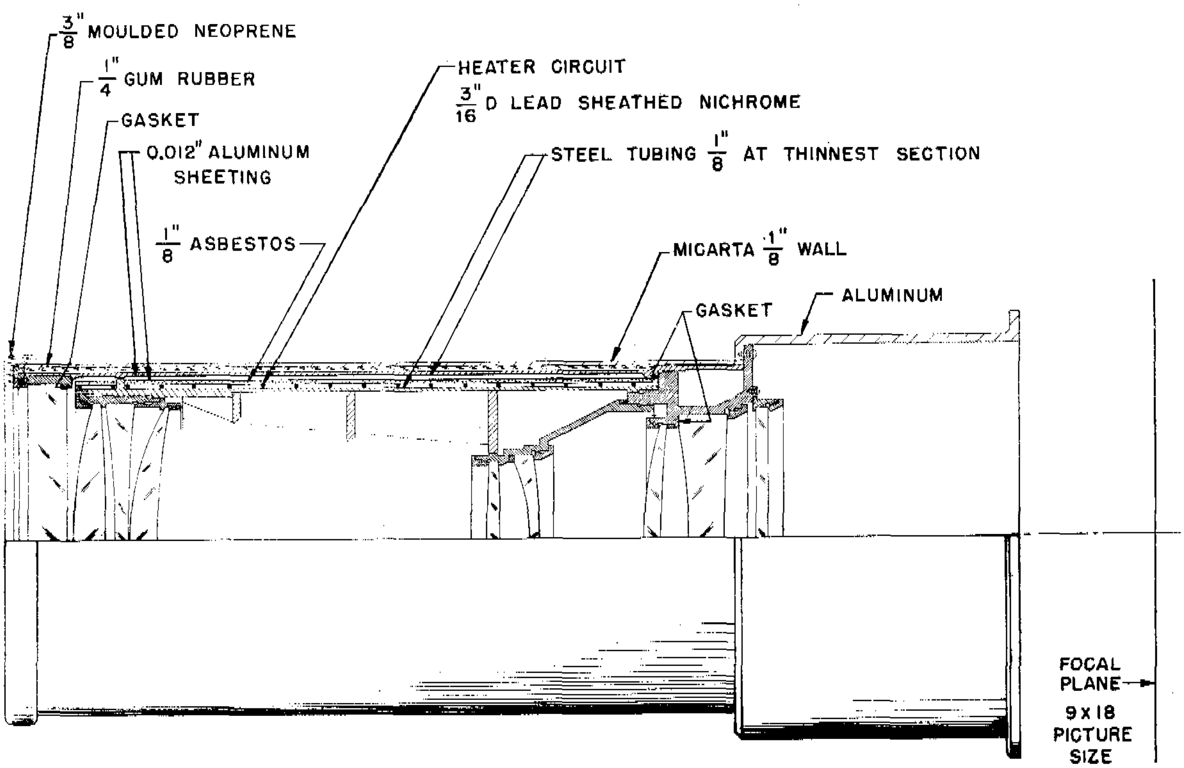

FIGURE 18. The 60-in. $f/5$ telephoto for 9x18.

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The tube supporting the atmosphere was to be lined on the inside with aluminum foil, opposed across the vacuum by foil covering the outside of the inner optical system. The mounting was therefore to resemble a vacuum flask. Calculations indicated that the probable slight heat loss could be restored by a thermostated 50-w heating circuit next to the optical tube.

Although the proposed mounting undoubtedly is more expensive and more difficult than ordinary designs, it was thought that the lens would only be used in precision reconnaissance and it was anticipated that production requirements would amount at most to perhaps a dozen units. Moreover, the cost of such a precision reconnaissance camera would still be far less than the cost of an F-13 photographic airplane.

At the end of World War II some of the optical elements had been finished, but glass had not yet been received for approximately half of the elements. The size of the elements and lack of heavy-duty machinery caused the optical work to proceed relatively slowly.

The 60-in. $f/5$ lens represents at this time the most advanced development of the NDRC lenses. The lessons taught by the extensive aerial camera testing during World War II indicate that lenses of great focal length properly made and used are capable of yielding an improvement in angular resolution which is in keeping with their focal length, and that linear resolution on the picture can reach at least 20 lines per mm on average days. It is therefore recommended that the two 60-in. prototypes be completed whenever practicable, and that the necessary careful attention to detail be given at all stages of the work. Particular attention should be given to "tight" but not "jammed" fits of lenses to their cells. Such fits can best be accomplished by reasonable tolerances on machine work followed by careful shimming. When properly mounted, the lens should resist turning in its cell but nevertheless be capable of being turned by some force. The Germans included the same requirement in their wartime lenses.

THE 100-IN., $f/10$, 9x18 FIGURE-4 ANASTIGMAT (HARVARD)[6]

In October 1942, it was decided that a 100-in. focal length lens should be added to the Harvard NDRC program. The only company manufacturing large disks of optical glass in this country at that time was the Bausch and Lomb Optical Company. The yield on large glass was so scanty and in such conflict with demands for optical glass from other consumers that it was decided not to exceed 10 in. diameter, which accordingly made $f/10$ the fastest possible lens speed.

Figure 19 shows the proposed lens system in the form of a "Figure-4" mount, a type peculiarly suited to this aperture and lens design. The folded design conserves space as well as

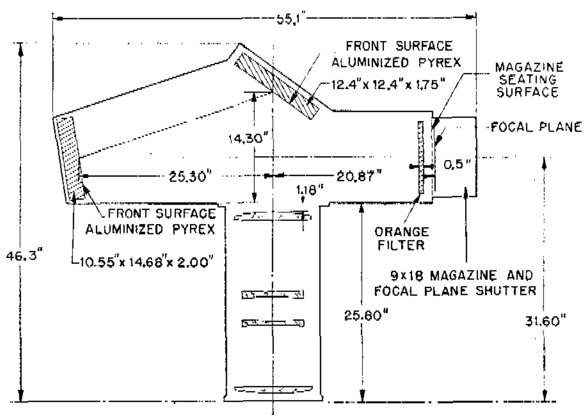

FIGURE 19. The 100-in. $f/10$ anastigmat.

possible for the purpose of aerial photography. Such a design unfortunately resembles the structure of a seismograph, in that the two mirrors multiply image vibrations.

The optical design was completed in June 1943. The lenses were made during the course of that year. The project was assigned very low priority on repeated occasions and consequently, during months at a time, went untouched. In 1945, however, interest reawakened, in view of the needs in the field for long-focus cameras. The lens was finished in the spring of 1945 and delivered to the Mount Wilson Observatory for testing.

A direct contract was made between the Army Air Forces and Mount Wilson for the design and fabrication of the camera itself, including a fast shutter for a 9x18 picture size. Although this work was not accomplished under NDRC, the mounting was designed to carry

the NDRC lens. In cooperation with Harvard, the mounting was so planned that a larger aperture lens of identical back focus could be substituted at any time for the $f/10$ lens. (See Figure 20.)

Design work was begun at Harvard on an $f/8$ apochromatic lens (see text that follows) for the same mounting.[7] The end of the war prevented completion of the design. Enough work had been accomplished, however, to point to the probable success of the endeavor. It was hoped that substitution of the $f/8$ aperture and the longer spectral range in sharp focus would combine to make shorter exposures possible, thus minimizing ground motion and vibration.

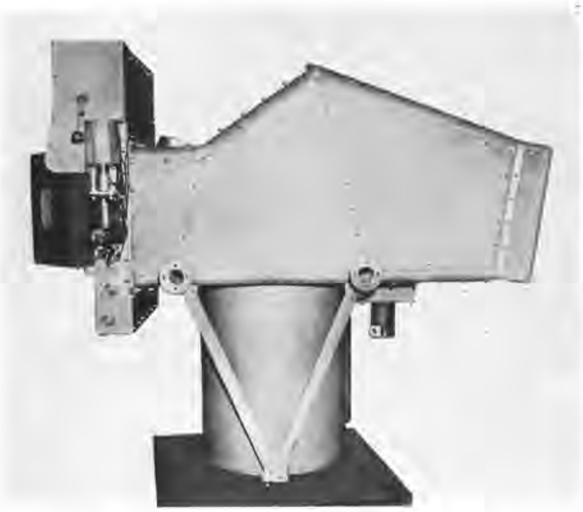

FIGURE 20. The 100-in. $f/10$ "Figure-4" anastigmat.

The 100-in. lens was tested both at Mount Wilson and at Eastman Kodak, under Contracts OEMsr-101 and OEMsr-392 respectively. The tests at Mount Wilson were carried out on the special optical bench. The overall length of the 100-in. lens was such that the nodal slide carrying the 100-in. lens barrel had to be mounted on a separate stand. Measurements of flatness of field and color and residual aberrations were carried out visually. Resolving powers at several contrasts were determined both visually and photographically.

Mount Wilson Results.[4a] 1. Astigmatism and field curvature, measured with respect to the best axial focus, are negligibly small for field angles below 4 degrees (about 7 in. off axis), but increase at larger angles to a maximum value in the corner of -0.35 mm radially and -1.1 mm tangentially. The variation is due to higher order astigmatism and varies at least as the fourth power of the field angle. Consequently, the effects of the aberration on resolution are felt only in the corners of the pictures.

2. Distortion is sufficiently small for any practical purpose to which the 100-in. lens might be put. The ray-tracing results on the design indicate that distortion in the corners amounts to only 0.012 mm pincushion type. The observed value appears to be 0.070 mm barrel type. Such small variations at such a long focal length are to be expected, unless special care is used during the final adjustment of the lens. Measurement is no less difficult.

3. Chromatic aberration. Lateral color is stated to be barely noticeable, but too small to be measured. Design figures indicate 0.013 mm in the corner with blue light nearer the axis than red. This residual design aberration can be reduced to less than one tenth of its present value by differential correction.

Longitudinal color is characteristic secondary spectrum, partially concealed by the Rayleigh limit depth of focus, with minimum focus at 6,350 A. The correction is optimum for use with orange filter, as incorporated in the mounting near the film. The chromatic difference of spherical aberration seems negligible. Although, visually, the secondary spectrum is very marked, photographically the effect is small.

4. Spherical aberration is veiled in the prototype lens by effects of inhomogeneity in one or more of the glass elements, or possibly by errors in surface figure of uneven character. Design figures show that the zonal aberration is within the Rayleigh limit. The zonal aberration is therefore nearly of optimum character in accordance with principles set down in the first part of this chapter.

5. The Mount Wilson report states that the resolving power (by the rule of reciprocals) in the center of the field is 80 per cent of the theoretical maximum for all contrasts, and better than 65 per cent of the theoretical maximum

[redacted]

for all field angles into the very corner of a 9x18 picture size.

Tests on two Pyrex optical flats indicate that, when edge-supported on felt in a suspended position as used, the mirrors are flat over the area used to at least one-half wave together, and over most of the area to better than one-quarter wave together. In view of the small area of the mirrors used by a beam converging to any single point image over the field, the flatness would appear to be adequate. For further studies of the 100-in. lens, see Section 1.4.

Apochromatic Aerial Lenses[8]

Under Contract OEMsr-474 Harvard University was requested to initiate investigations involving the use of synthetic fluorite for the purpose of removing secondary spectrum from aerial camera lenses. Calculations were begun in the fall of 1942 for the purpose of testing the performance of fluorite as an optical material. Successful results obtained with several telescope apochromatic objectives of long focal length showed that it would be feasible to use fluorite for the purpose specified.

Calculations were completed in the spring of 1943 on two types of apochromatic $f/8$ aerial lenses of 36 in. focal length. The first of these is shown in Figure 21. The "short barrel" form was disappointing as to design, and was made up as an interim lens. It proved difficult to flatten the field without leaving excessive off-axis coma, owing to the low index of refraction of the materials used, especially fluorite.

The lens was flight-tested at Wright Field on several occasions, on Super-XX and on color film. In spite of the large comatic flare, the lens gave fairly good aerial pictures. "Even with less than one-third of the light in the effective image, the pictures seemed sharp to the eye." The aberration curves from the lens design show that at the side of the picture the total spread of rays from outward oblique coma amounted to 0.3 mm. The fact that the pictures were deemed fairly good is consistent with the discussions in Section 1.1.

Shortly afterwards, in April 1943, a more satisfactory fluorite apochromatic design was finished. During May 1943, a "long barrel" $f/8$ apochromat of 36 in. focal length was made up and delivered to Wright Field for aerial tests. In the laboratory at Harvard, visual tests showed the lens to be of high quality, especially for its freedom from color. The predominant residual aberrations were rapidly increasing astigmatism and vignetting in the corners of the 9x9 picture area. Rather than decrease the quality of the larger area of the picture, the performance in the corners was sacrificed. The final lens was deemed to cover satisfactorily the 9-in. included circle. It is apparent that the lens system could not be used for 9x18 coverage without further and more complicated design work.

During the summer of 1943, a second model was completed according to the same design. As in the first case, this model was found to yield

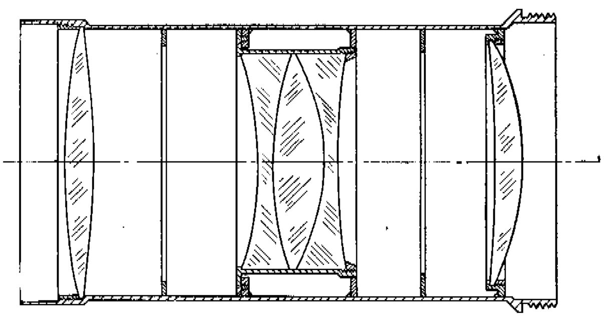

FIGURE 21. The 36-in. $f/8$ fluorite apochromatic aerial lens (short barrel).

sharp images over a 9-in. circle. Figure 22 shows a cross-sectional view of the lens system.

Cold-chamber measures in the Harvard laboratory showed a great change of focal position with temperature, due mostly to the single fluorite element. Over a range from room temperature to −73 C, the back focus shortened 0.215 in. (see Figure 23), which at $f/8$ would be disastrous. For such a lens, thermostating is obviously essential.

Although the lens was tested with focus runs in the air at Wright Field, various difficulties prevented good aerial pictures. Laboratory measures, however, indicated a high level of performance. The lens was described in a Wright Field report as unsuited to military photography, primarily because of excessive camera length and change of focus with temperature.

[redacted]

Extensive testing of the 36-in. lens was carried out at the Mount Wilson Observatory.[9] Figures 24, 25, and 26 show the results obtained on the optical bench. All tests were carried out with slit illumination provided by a high-pressure mercury lamp with yellow filter transmitting wavelengths longer than 4,800 A. The energy distribution in the light source approximated daylight quality.

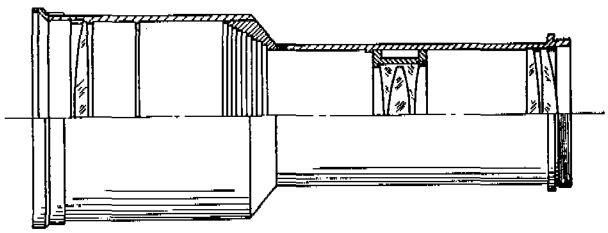

FIGURE 22. The 36-in. $f/8$ fluorite apochromatic aerial lens (long barrel).

Results. 1. Color aberrations. Visual measurements made of longitudinal color aberration indicate that the secondary spectrum has been reduced to the sufficiently low value of 20 per cent of the normal curve for glass objectives, but not entirely eliminated. The maximum departure from mean focus between 5,000 and 6,700 A on axis amounts to 0.0001 of the focal length, which at $f/8$ is sufficiently good for all purposes of aerial photography. The chromatic difference of spherical aberration seems negligibly small. Figure 25 shows the color curves for three field angles. The change in correction with field angles seems inappreciable.

No direct measures of lateral color have been reported. However, inspection of the monochromatic astigmatism at 5,450 A, in comparison with heterochromatic astigmatism with yellow filter, shows the latter to give better definition tangentially. Such a result cannot happen unless the lens is well corrected for astigmatism in orange and red light, and is sufficiently free of lateral color. Design figures indicate extremely small lateral color, although exact ray-tracing values to the corner of the field in several colors are not at hand. Indeed, visual inspection in the Harvard laboratory indicated that residual chromatic variation of astigmatism was prominent in this lens, although not of large magnitude. The error arises from the large front air space, required for the correction of other more important aberrations.

2. Astigmatism and curvature of field. These are inappreciable over an 8-in. diameter circle. Outside this circle, however, the rapid growth of fifth-order astigmatism produces progressive forward curvature, especially of tangential lines. The vignetting present maintains the resolution but in itself must be considered an aberration and disadvantageous. The 80× photomicrographs of star images given in the Mount Wilson report[9a] show that the concentration of light into point images on a flat focal plane has been very well achieved over an 8-in. diameter circle, but that the corners of the picture fall to ordinary levels of resolution.

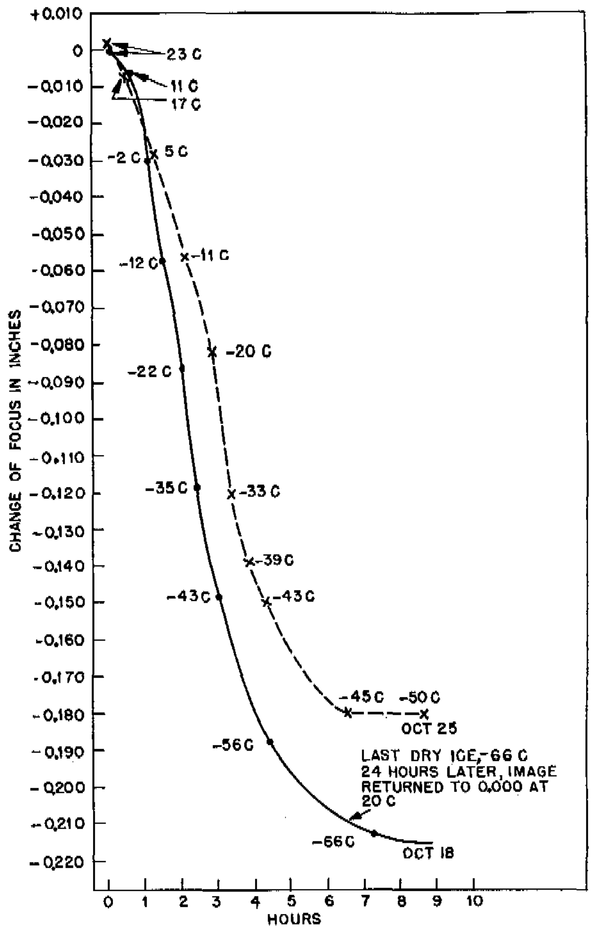

FIGURE 23. Cold-chamber observations on focus of fluorite apochromat.

3. Distortion. Over the 9x9 picture size, dis-

tortion was found to amount to less than 0.005 mm over most of the field, increasing to about 0.020 mm pincushion type in the corner. These minute values are in good agreement with calculations presented in the Harvard report.[8]

4. Resolution. Figures 24 and 26 show the results of extremely well determined visual and photographic resolution tests made at several

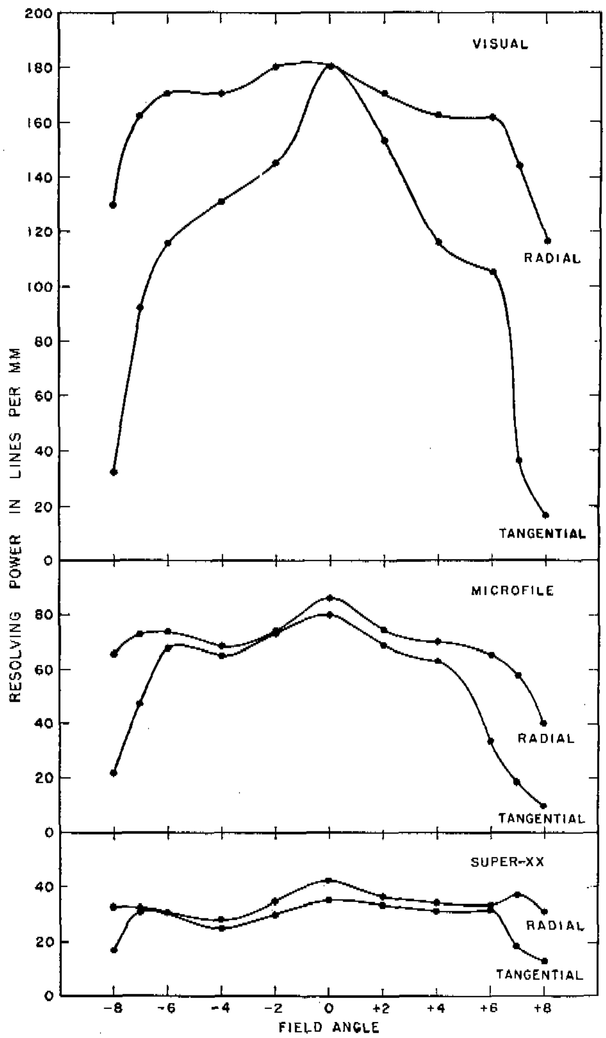

FIGURE 24. Dependence of resolving power on field angle.

contrasts by Mount Wilson and described in their report.[9] It is evident that the lens is well corrected in the center of the field, but that the visual quality at the center is concealed on Super-XX by the film itself. The depth of focus versus resolution curves for Super-XX and Microfile indicate that almost all of the effective light of the $f/8$ aperture lies within the Rayleigh limit in the center of the field.

According to the Mount Wilson conclusions, the resolving power reached 96 per cent of the theoretical maximum in the center of the field, and was better than 75 per cent of the theoretical maximum for a field 8 in. in diameter.

Aerial Tests. In addition to the unfruitful tests made in the air at Wright Field, the second long-barrel model was tested at length in 1945 under the Harvard contract.[10] The difficulties encountered at Wright Field were partially overcome by revision of the mounting and by careful thermostating of the entire mount. Focusing runs at 10,000 ft over Orange, Massachusetts, resulted in an average maximum resolution of 32 lines per mm across the line of flight. These tests were made with a K-22 camera and yellow filter, and a shutter speed of $\frac{1}{350}$ sec on Pan-X. In spite of the high state of correction for color, the maximum resolution figures for the fluorite lens did not reach the best results achieved with the 40-in. $f/5$ telephoto lens. One must conclude that the $f/5$ monochromatic resolution was enough of an advantage to overcome the superior color correction of the $f/8$ fluorite lens, and particularly that the 40-in. lens was better mounted for aerial purposes. The fluorite lens undoubtedly would be much superior to the 40-in. for color photography in view of its high correction over an extended spectral range and in view of the disadvantage of telephoto designs for even normal color correction.

The 48-in., f/8, 9x9 Apochromat.[8a] In order to overcome both change of focus and length, the Harvard laboratory planned a 48-in. U-shape camera with thermostated heating system. Although assigned to low priority on the program, the optical parts for this lens, including two Pyrex mirrors of suitable size and shape, were completed. No mounting was ever constructed. The picture size of 9x9 was retained, which in further work should be increased to 9x18 with great emphasis on low vignetting.

Discussion. Apochromatic systems will ultimately be required for perfected aerial photography. It is probable that at the present time the loss of contrast due to secondary spectrum

is less important than vibration and other limiting factors. For color photography and for lenses of very large aperture, however, apochromatic systems will be of great value. Such a lens would be of about 10 in. aperture, used either for color work or for night photography without filter.

The Harvard 36-in., $f/8$, 9x18 Wide-Angle Telephoto[11]

One of the most important problems undertaken by Section 16.1 of NDRC in the last 12 months of World War II was a 36-in. focal length $f/8$ telephoto for the K-18 (9x18) as prepared for production. Only two types of glass were used, distributed among five elements. The design was much more suited to mass production than the 40-in. $f/5$ automatic lens, and consequently was felt to be a lens of general utility, like the British 36-in. for 7x9. Limitation of the aperture to $f/8$ resulted in improved resolution and reduced vignetting. Indeed, the first prototype had no appreciable vignetting. The second prototype had vignetting which, while less than in the standard 24-in. lens, was not as small as desirable.

Discussion. The wide-angle telephoto has the largest coverage at 36 in. focal length yet used

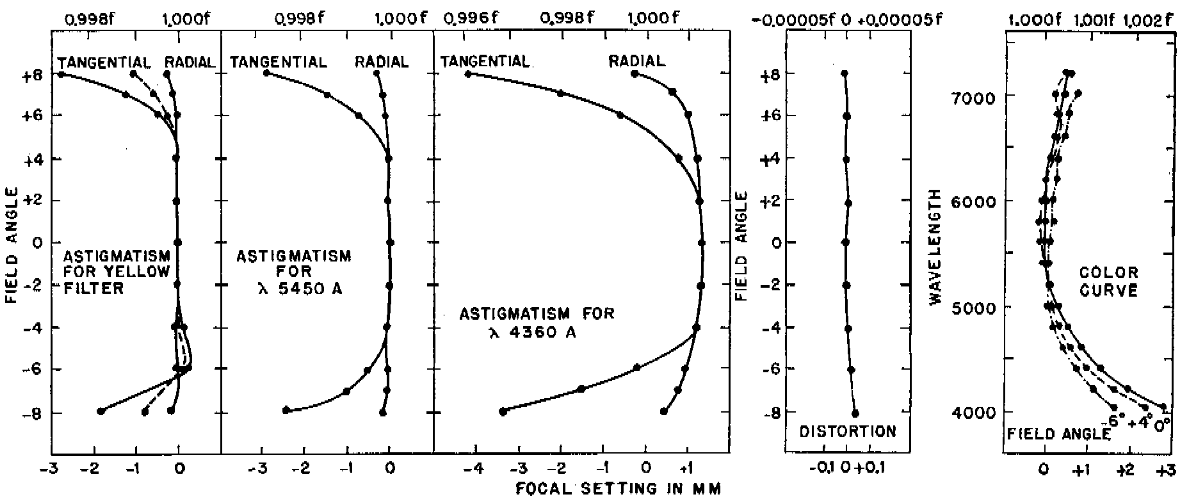

Figure 25. Astigmatism, distortion, and color curves.

camera (see Figure 27). In the field, the dual need appeared for large-scale contact printing and compact, light equipment. It was felt that a replacement telephoto lens for the K-18 Tessar would answer the problem adequately, even though the resolution achieved might not be superior or perhaps quite as good as that already obtained with the standard 24-in. lenses.

Design. The design of the 36-in. telephoto was worked out at the Harvard laboratory in the summer of 1944 and a prototype was delivered in December of that year. Visual laboratory tests at Harvard indicated that further improvement might be made. An improved design was worked out and a second prototype was made and delivered to Wright Field in April 1945.

Figure 28 shows the second prototype design in the air. The 36-in. telephoto was designed to fulfill a sudden need, and its design was restricted by the need to adapt it to the K-18 camera. With the appearance of new types of optical materials and under peacetime conditions, there is every reason to believe that considerable improvement can be made in both the speed and covering power of the 36-in. lens. It is believed that future efforts should compromise neither field nor vignetting, but should concentrate on improved resolution and increased speed, in accordance with the principles outlined in the introduction. (See Section 1.1.)

Tests. Tests made in the air on the first prototype at Midland, Texas, in February 1945, proved that photographs made with the lens were comparable with the linear resolution given by the standard 24-in. lens, and therefore

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possessed somewhat superior angular and ground resolution. Laboratory measures indicated still greater superiority, even on a linear basis. The use of the between-the-lens shutter,

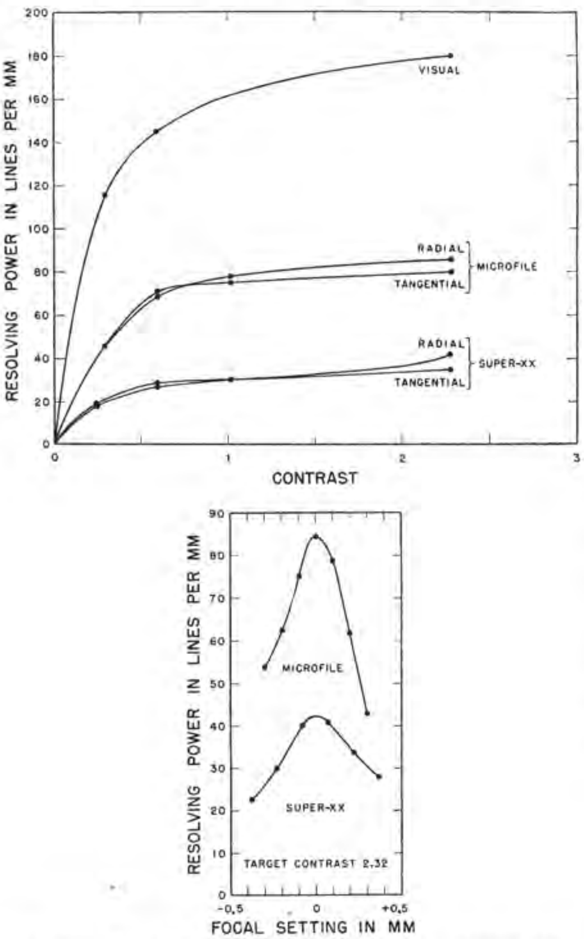

FIGURE 26. Dependence of resolving power on contrast and depth of focus.

which gave an exposure of $\frac{1}{150}$ sec, limited the aerial performance of the 36-in. lens in tests to date.

Laboratory tests were carried out at the Eastman Kodak Company late in 1945. Wedge patterns and resolution measurements are reproduced in Section 1.4.

UNCOMPLETED LENS DESIGNS AT HARVARD

On the Harvard program for 1946 there were several long focal length lenses some of which were only partially designed or constructed at the end of the war. These will be described briefly.

The 100-in., f/8, 9x18 Apochromat.[7a] A 100-in. $f/8$ apochromat, for 9x18 picture size, was investigated to serve as a replacement lens of faster speed for the 100-in., $f/10$, 9x18 focal length lens for the "Figure-4" camera. The apochromatic correction was not to be obtained by means of fluorite but by use of hyperchromatic combinations of ordinary crown and flint glasses. Calculations presented in report form show that by making use of heavy flint glass for positive elements, one can obtain not only a great contribution to the Petzval sum for better flatness of field, but can also eliminate almost entirely the troublesome secondary spectrum. No final design has been submitted, but it is recommended that such a lens be added to any continuation of a program in aerial photography intended for extreme altitudes.

The 36-in., f/8, 9x18 Anastigmat.[7b] An uncompleted lens design of great promise was a 36-in. focal length $f/8$ anastigmat, modeled along the lines of the 6-element Planar. In spite of the use of ordinary glass types, it proved possible to obtain an extremely flat field of high correction. No final design has been submitted, but it appears from the Harvard report that the completed lens should give results greatly superior to those obtained with the 36-

FIGURE 27. The 36-in. $f/8$ telephoto in the K-18.

in., $f/8$ telephoto lens. The anastigmatic form is intended to provide a 9x18 picture almost free of vignetting. The use of six elements makes possible unusually good correction for

oblique spherical aberration. Owing to the symmetry of the lens, exceptional correction for unsymmetrical errors is possible, relative to telephoto designs. It is recommended strongly that this type of lens or its equivalent be pursued to the limit with improved optical materials in

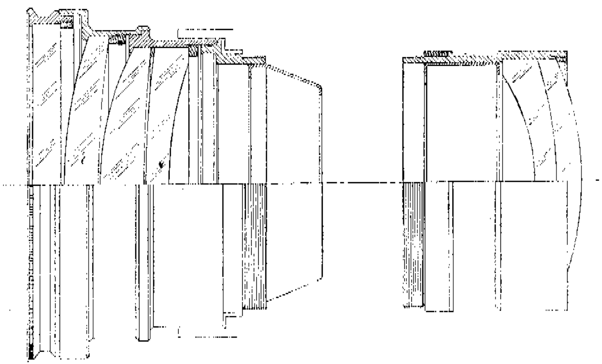

FIGURE 28. The 36-in. $f/8$ telephoto for 9x18.

order that the Army Air Forces may have at their disposal a lens optimum in all respects, except perhaps focal length. Of all the designs submitted during the war, this lens holds forth best promise of meeting the stringent ultimate requirements outlined in the introduction. (See Section 1.1.) It is felt that $f/8$ is too slow and that effort should be made to increase the speed to $f/5$.

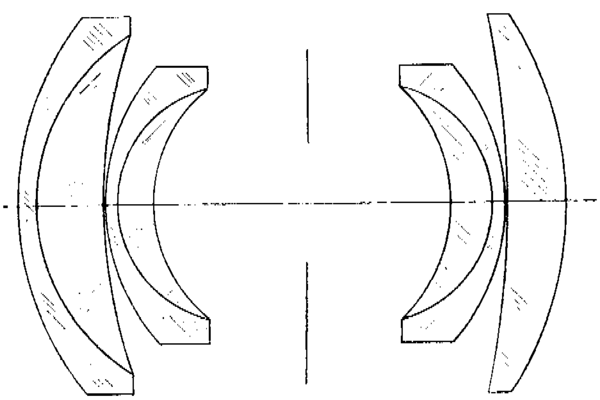

FIGURE 29. A preliminary design for a 12-in. $f/5$ for 9x9.

The 12-in., f/5, 9x9 Anastigmat.[7c] This design was planned to explore the possibilities of providing a lens of improved definition for the standard 12-in. camera with 9x9 picture size. Figure 29 shows a cross section of the design in its present unfinished state. The design is probably much more elaborate than is necessary to achieve the desired result. The lens described, however, shows promise of an extremely flat field free from astigmatism, and in addition a high state of correction for oblique aberration. The symmetry of the design is very favorable for excellent correction of the unsymmetrical aberrations, provided that some attempt is made to eliminate the oblique coma introduced by the first doublet.

1.3.2 Lenses Developed for Night Photography

Most of the night photographic work carried on in the war made use of flash bombs of increasing brilliance set off at the proper altitude, and of capping shutters activated by photoelectric pickup of the early light from the bomb. In the latter respect, difficulty was experienced with exposures which were tripped and fogged by enemy searchlights.

A number of lens forms were developed by NDRC for improvement in night photography. Standard equipment developed outside NDRC included mass production of a 7-in. $f/2.5$ lens for 5x5, used with a focal plane shutter in the K-24 camera, and a 12-in. $f/2.5$ lens for 9x9, used in the K-19 camera. An 8-in. focal length $f/1.5$ lens designed at Eastman for the Air Forces, quite apart from NDRC, was produced in limited numbers by the Canadians and the British. Little use was made of this lens by the Army Air Forces, owing to a trend toward greater focal lengths.

THE 6-IN., $f/1$ CURVED-FIELD LENS[12] (U. OF ROCHESTER)

One of the most promising lenses was a 6-in. $f/1$ lens covering a 40-degree field, which was developed at the University of Rochester. Exceptional optical correction was made possible by designing the lens for a curved focal surface, nearly spherical, and equal in radius to about 0.8 of the focal length. Although the curved field introduced mechanical problems, experiments made at the Institute of Optics of the University of Rochester under Contract OEMsr-160 proved that ordinary roll film could

be stretched into the curved focal surface backing-cup by means of applied air pressure up to 20 psi. It was discovered that film so stretched regains its shape and can be contact-printed in the usual way. Consequently, in spite of the curved field, a means has been found to provide very material improvement in night photography. It is highly recommended that future work exploit these possibilities to the full, particularly along lines of slightly moderated focal curvature for wide angular coverage.

Figure 30 shows a cross-sectional view of the lens design. The form is based essentially on an

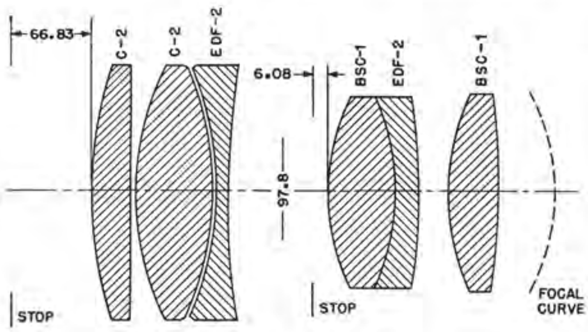

FIGURE 30. The 6-in. $f/1$ night lens with curved field.

enlarged microscope objective, corrected for astigmatism. The use of all positive elements, especially of ordinary glass pairs for achromatism, produces the large curvature of field but at the same time removes astigmatism and gains in net power. The rear positive elements tend to decrease both the zonal aberration of the front triplet and the secondary spectrum of the front achromatic triplet system. Both corrections are exceedingly good, and more than adequate for the purpose.

Figure 31 shows about a 100× enlargement of a star image, photographed at several field angles inside and outside focus and at the best focal setting, made with a 50-mm lens that was actually constructed as a pilot model. Over at least a 30-degree total field the images are small enough to get peak resolution from Tri-X night film at the contrasts likely to be encountered at night. Under the best conditions there is no reason why the night pictures should not be as sharp as day pictures, especially if shorter exposures or sweep mounts can be used.

Discussion. The 6-in. $f/1$ night lens should be completed at the earliest opportunity and tested at length. It is very probable that high-altitude night photography, particularly with flash units, will require lenses of this speed and quality. Since roll film can be used with the apparatus, no objection on the basis of maximum convenience should be allowed to stand in the way of an important forward step in night resolution and coverage.

THE 7-IN., $f/2.5$, 5x5 LENSES FOR NIGHT PHOTOGRAPHY

Several lens types of slightly differing specifications were designed and constructed at Polaroid and Harvard to supplement and possibly to improve the 7-in. $f/2.5$ standard Aero-Ektar for the K-24 camera. In 1942, production of the Ektar lenses was behind the large Army schedules and behind the large production of camera units. At the request of the Army, NDRC undertook to provide some supplementary lenses for the same purpose and to meet the production requirements temporarily until

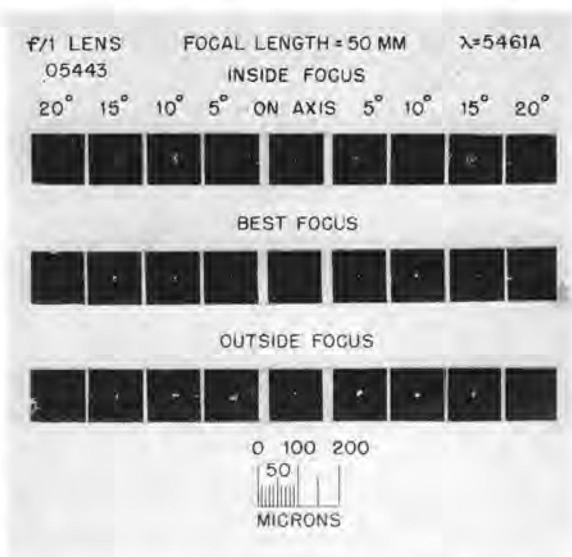

FIGURE 31. Photomicrographs of star tests of the $f/1$ night lens with curved film.

the standard lenses appeared. In the interest of quick design and production, tolerances on performance were therefore relaxed.

None of the lens types for the K-24 camera developed under the Polaroid and Harvard con-

tracts were actually put into production by the Army, owing mostly to later rapid strides in production of the standard lens.

The 7-in., f/3, 5x5 Plastic Lens (Polaroid).[13] The design of this lens is shown in Figure 32. The lens is capable of high axial performance, and has a flat field in the neighborhood of the axis. Most probably, off-axis performance suffers from excessive astigmatism. All lens surfaces are spherical in this design, and all elements are of plastic. The off-axis astigmatism seems indicated also by resolution figures from the Polaroid tests. The lens resolved 28 lines at the center of the field, 13 lines at half field, and 3 lines at full field at 46 degrees total.

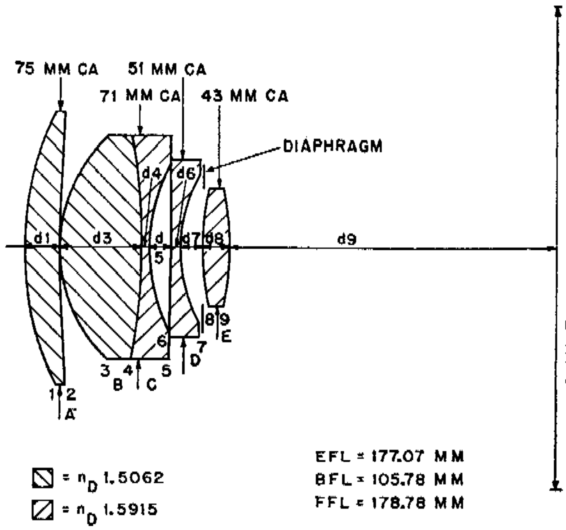

FIGURE 32. The 7-in. $f/3$ plastic lens for 5x5.

The 7.5-in., f/2.8, 5x5 Plastic Lens (Polaroid).[13a] The lens form is shown in Figure 33. This design has been developed by Polaroid as a means of countering the troublesome low indices of the plastic elements. It makes use of a DBC-1 nearly equiconvex positive element behind the stop. The negative rear element lens is intermediate between a field-flattener and a proper member of the lens barrel. In the position where it is placed, good use can be made of the element for optical corrections.

Three models of the $f/2.8$ lens system were made and delivered. After several adjustments, always necessary in a new design, the $f/2.8$ lens was found to resolve 50 lines per mm on the axis, and 30 lines per mm 2.5 in. off axis.

Extensive tests of the $f/2.8$ Polaroid lens in comparison with the Aero-Ektar lens were carried out at Mount Wilson. In general the Polaroid lens seems better than the Aero-Ektar near the optical axis, but in the outer part of the field its aberrations, chiefly tangential astigmatism, increase more rapidly than the Aero-Ektar residual errors. The differences in part are a choice of balancing of errors. If the Ektar lens were stopped down to $f/2.8$ and redesigned for flatter central field at the expense of the corner performance, then its performance in the central region would be at least as good as that of the Polaroid $f/2.8$ lens. On the other hand, it is doubtful whether the Polaroid lens could be balanced for improvement of the corner images without decreasing the quality of the central region considerably below that of the Aero-

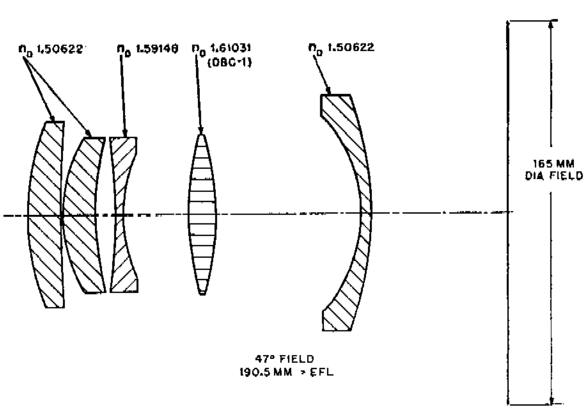

FIGURE 33. The 7.5-in. $f/2.8$ plastic lens for 5x5.

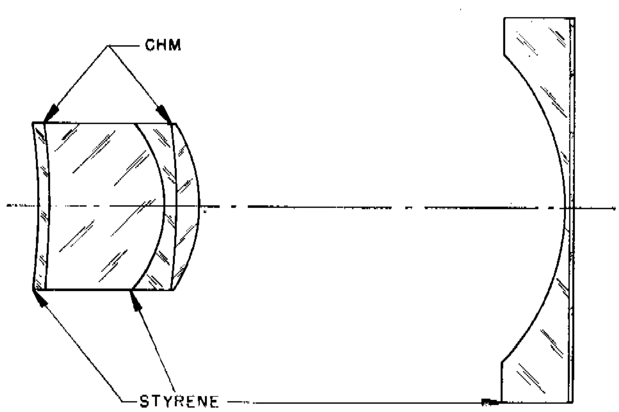

FIGURE 34. The 7-in. $f/2.5$ plastic lens for 5x5.

[redacted]

Ektar lens, particularly if the aperture were increased to $f/2.5$. The greater symmetry of the Ektar lens, and particularly the coincidence of the radial and tangential surfaces over most of the field, gives it a strong advantage for uniform good performance.

The 7-in., f/2.5, 5x5 Lens (Harvard-Polaroid).[14] In 1942, an early plastic design, as shown in Figure 34, was made up and tested at Wright Field. The front two surfaces and also the front surface of the field-flattener are aspheric. The lens is corrected accurately for spherical aberration at every zone. In addition, since Polaroid plastics were used, the secondary spectrum is approximately one-half of the usual amount. The design incorporates into a Schmidt-like lens system, with only two air-plastic surfaces, an aspheric field-flattener so shaped that the mean focal surface is flat over the entire field. The Harvard report states that the astigmatic difference is about 0.7 mm in the very corner, with the tangential curvature about 0.5 mm toward the lens, and the sagittal curvature about 0.2 mm away from the lens. Decrease of the astigmatic difference toward the axis follows the fourth power of the field angle. Vignetting is very slight. Distortion is small.

The prototype lens made in 1942 was experimental both in the sense of plastic molding and of aspheric work. The best resolution given by the lens on axis was 20 lines per mm, although in principle the resolution should have been limited only by diffraction. No satisfactory aerial pictures were obtained with the first model, and the project was dropped.

Discussion. Of the plastic lenses only the $f/2.8$ seems worth further consideration. The subject of plastic lenses has been viewed in so many ways that one cannot here make a distinction between plastic and glass. Should plastic lenses be required, however, it would appear from the above that the $f/2.8$ deserves further attention.

The 7-in., f/2.5, 5x5 Lenses (Harvard).[14a] A series of 7-in. $f/2.5$ lenses was designed and constructed by the Harvard laboratory, for use with the K-24 camera, during 1942 and early 1943. The first three models (A, B, and C) were constructed of ophthalmic glass for the purpose of maximum production, and for this purpose were designed with the shallowest possible curves for adequate performance. A fourth model (D) of optical glass was designed and made up during the winter of 1942 to 43. This design came nearer to production than any of the other $f/2.5$ lenses. Indeed, glass was ordered for 1,500 units, but later the order was reduced to 88 units, made up at Harvard.

Figure 35 shows the lens forms of design D. The third and fourth are modeled on the Biotar type, which forms the basis of many modern lens forms. The Biotar design, although capable of great speed, is afflicted by higher order astigmatism and oblique spherical aberration of considerable amount. The Ektar 7-in. lens is related to the Biotar form, except that the use of rare-earth glass has made it possible to use thinner elements around the stop, which in turn reduces the higher order astigmatism difference. Oblique spherical aberration in the Ektar is large and a major factor in limiting the performance of the lens. Curvature of field of the Ektar is also large and a definite limitation on its performance.

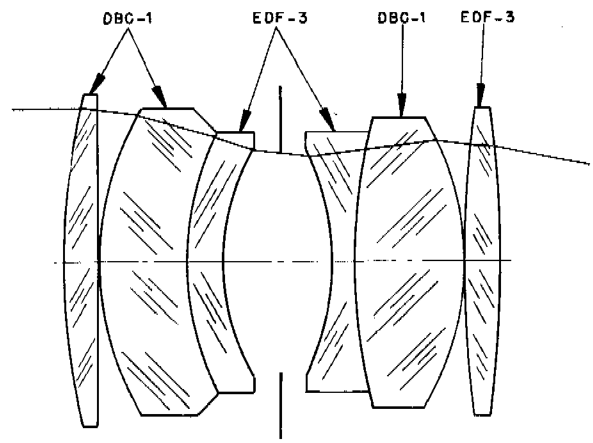

FIGURE 35. The 7-in. $f/2.5$ night lens for 5x5, model D.

Like the Polaroid lenses, the Harvard $f/2.5$ lenses are afflicted with higher order tangential astigmatism as a consequence, partly, of the Army request for the shallowest possible curves for maximum production. The Harvard report[14] states that the oblique spherical aberration of models C and D is smaller than in the case of the Aero-Ektar but that the astigmatic difference is larger. The mean focal sur-

[redacted]

face of the Harvard lens is flatter than the mean focal surface of the Ektar, but on this surface the optical resolution is inferior. The reduced oblique spherical aberration actually tends to accentuate the astigmatism, with the net result somewhat lowered resolution. The shallow curves result in a central image of great purity in Harvard models C and D.

The Harvard lenses model C and D present a novel form of construction in that the rear element consists of a high-index flint glass. The use of a highly dispersive flint glass for a positive element introduces a considerable amount of color which is overcome by a hyperchromatic doublet after the stop. The high index of the flint positive element, in spite of the color-correcting flint negative element, produces a net gain in the Petzval sum. Since the Petzval sum of the lens system is still fairly large, the overall result is very shallow curves and an excellent central correction.

One other Harvard $f/2.5$ lens design was submitted, but by this time no further production of $f/2.5$ lenses was contemplated. This lens design attempted to overcome some of the aberrations of the earlier shallow-curve models, but requires further study. Heavy-index glasses were used for the purpose of reducing the hitherto too large Petzval sum, but at a cost of rather complicated construction. It is probable from the performance figures that further design work might convert the lens into a well corrected system. The use of high-index flint glass for long focal length lenses is attended by large absorption. Most probably, better performance can be achieved from an overall point of view by means of the high-index white glasses now available and by close attention to optimum image structure.

Figure 36 reproduces this lens form. Note that the greater symmetry around the stop is likely, although not sure, to lead to better correction at large field angles. The unsymmetrical doublet at the front of the barrel leads to comatic flare off axis, but, as described in the introduction, the resulting performance is likely to be better than if only astigmatism were retained. The standard Tessar makes similar substitution and achieves good performance with large coverage.

No laboratory tests are available on the various Harvard $f/2.5$ lenses except those made at Wright Field. Briefly, for model D, tangential resolution at high contrast starts at 53 lines per mm on axis, decreasing gradually to 10 lines per mm, and then increasing once more to 24 lines per mm. The radial resolution, owing to a slight error in centering, begins at 42 lines per

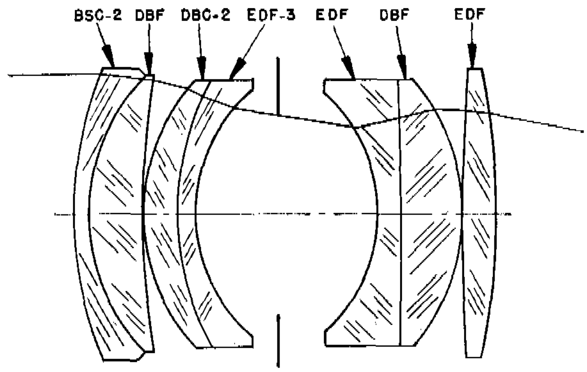

FIGURE 36. The 7-in. $f/2.5$ night lens for 5x5, Model E.

mm on axis in the model tested, falls slowly to about 20 lines per mm at 22.5 degrees off axis, and then decreases very rapidly. At the usual low contrast of night photography, such resolution is probably adequate for general use, but not good enough for future specialized work.

Discussion. Although the Rochester $f/1$ lens seems the most likely to provide spectacular improvement in future night photography, it seems well worth while to continue development of faster and better conventional lenses. It is believed that none of the $f/2.5$ lenses described above has exhausted all possibilities, particularly should new optical materials become available.

As a goal in the near future, the Air Forces might well request bids on an $f/2$ lens of image quality at least as good as that obtained at present from the standard $f/2.5$ Ektar. Specifications should be written around an effective $f/2$ speed in order that superior image quality may not be obtained at the expense of transmission losses. For some time to come, it would appear that a 12-in. focal length $f/2$ lens, with 9x9 coverage, is a worth-while goal. The use of a field-flattener should not be ruled out, provided the field-flattener is more than 1 in. away from the

film. The use of a curved backing-plate, however, would be preferable.

1.3.3 Lenses for Specialized Purposes (Harvard)

TELEPHOTO SCOUT CAMERA, 48-IN., *f*/8, 3¼x4¼ LENS[7d]

In 1945, need developed in the Services for some means of recording by hand in the air camera objects which are of interest as seen through binoculars. This suggested the development of a combined binocular-camera arrangement, boresighted to record on 3¼x4¼ picture size approximately the field of view of the binocular. In the model planned by Harvard, a 48-in. focal length *f*/8 telephoto lens was to be used. The field was to be somewhat smaller than that of the binocular in order to keep the overall size within reasonable limits. It was felt that the recording of as much detail as could be seen on selected objects with 10x50 binoculars might be achieved with a 48-in. lens and that this was much more important than covering the whole field.

Figure 37 shows a cross-sectional view of the proposed scout camera. No detailed ray-tracing calculations are available other than computations showing that the total inward radial comatic flare in the corner of the picture amounts to about 0.1 mm. In view of the *f*/8 speed, it is probable that a comatic extension of this slight magnitude will cause no great deterioration in resolution or contrast.

The lens form is modeled after the *f*/6.3 Zeiss-Telikon by substitution of the American glasses most nearly similar. The 4-element telephoto lens of this form is extremely sensitive to variations in curves, indices, and lens thicknesses, more so than one would suppose from the speed rating. Consequently, adaptation of the Telikon lens to 1945 American glasses required almost as much redesign as if started from the beginning.

The lateral color has been reduced to secondary spectrum in the lateral color, with minimum magnification at the D line. Field flatness and astigmatism are optimum for the size of picture adopted. Vignetting is small. It is evident from the design figures of the Harvard report that the resolution of the scout camera over the field can be expected to be 20 or more lines per mm in the air, provided exposure times as short as $\frac{1}{350}$ sec can be used.

Recommendations. The 48-in. focal length scout camera may be too large for general utility. It would seem worth while to design a 24-in. model for the same picture size, in order that the full field (7 degrees) of the binoculars be covered. The Telikon lens form, when worked to its limit of performance, should be capable of providing such an angular coverage with sharp resolution and good contrast.

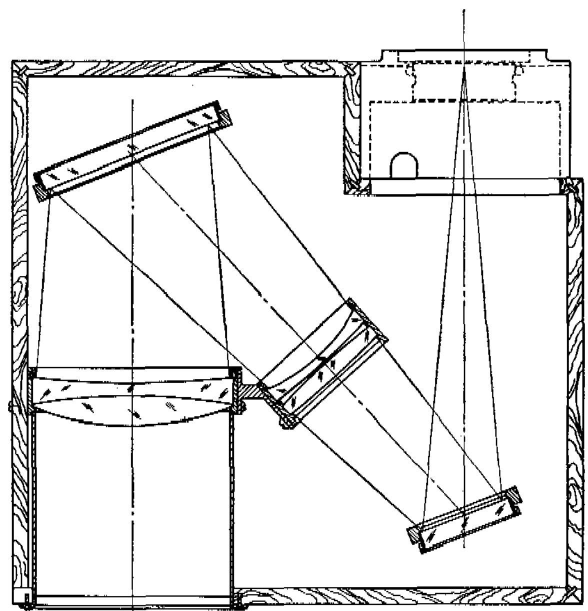

FIGURE 37. The scout camera.

COMPOSITE *f*/6 TRIPLET LENSES FOR THE K-18 CAMERA[7e]

For use with the aerial testing program under the Harvard contract, a lens design for a Cooke triplet of small angular field and high quality was developed. This design was to be made up in 48-, 24-, 12-, and 6-in. focal lengths. All of these lenses were to be mounted in a single rigid assembly and used with a single focal plane shutter and A-7, 9x18 magazine. Each lens was to be of essentially perfect quality across the chosen area of film assigned to it. It was believed that such a test-lens assembly

could lead to exact evaluation of the influence of haze on resolution in the air, as well as the practical dependence of resolution on focal length. Difficulties of proper focal setting for each focal length were to be overcome by thermostating and by focus runs in the air.

Figure 38 shows a schematic view of the contemplated system. In order to retain the thermostated heat, the front of the assembly was to be covered by a plane-parallel window of optical quality.

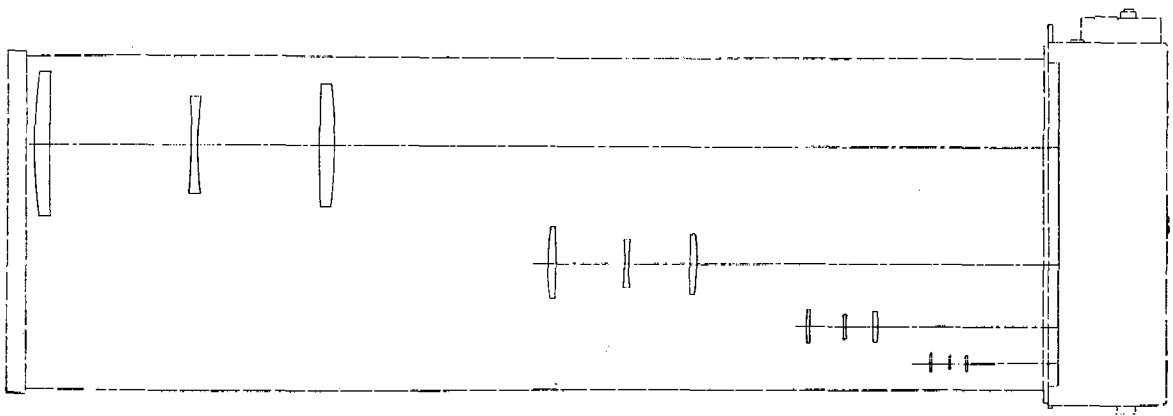

FIGURE 38. An $f/6$ test system.

The triplet design adopted is optimum for good axial correction and small angular field of high quality. The relatively long barrel length leads to large tangential astigmatism far off axis, but for the present problem the higher order field errors can be ignored. Exact ray-tracing curves are provided on axis and in the corner of the restricted field. These curves are of nearly identical shape and are very close to the Rayleigh limit. It was planned that any residual flare of spherical aberration in the 48-in. $f/6$ lens would be figured out of the lens.

LENS FOR PROJECTION PRINTING[7f]

The flight test program at Harvard under Contract OEMsr-474 indicated a need for better printing of high-resolution negatives. Experiments made with contact point-source printing and contact diffuse printing indicated that the best negatives lose a considerable fraction of their resolution and contrast in the printing process, especially on the standard Army printer. It was concluded that projection printing equipment at 1.5× enlargement with condenser illumination should be designed and constructed. The end of World War II prevented much progress along these lines. Later work has indicated that the standard printer yields a resolution of 60 lines/mm on contact printing of an extremely fine, high contrast target.

Because of the resolution possible with projection lenses, especially at one-to-one ratio, or at small enlargement, it would seem that much of the negative resolution can be preserved in the print. The Harvard plan was to enlarge by 1.5× in order to remove most of the tendency of the printing paper to limit resolution. The plan should be pursued in further work.

36-IN., $f/11$, 9x18 APOCHROMATIC TELEPHOTO[8b]

Following the completion of the 36-in. $f/8$ telephoto for the K-18 camera, tests at Wright Field on color film proved that the telephoto with its correction at D was not suited for color work. Calculations were begun at Harvard with the view to designing an apochromatic 36-in. lens, making use of either barium fluoride or calcium fluoride. The calculations were only provisional. Paraxial color calculations indicated that a high degree of color correction can be obtained, even in a telephoto construction. The Harvard report states that an apochromatic telephoto at $f/11$ can be designed when needed. This design would follow along the lines of the 4-element Telikon, and

[redacted]

would use two elements of one or the other crystal. In order to protect the leading crystal it would probably be necessary to enclose the entire lens system by means of a front window.

12-in., $f/4.5$, 9x18 Anastigmat for the K-18 Camera[7g]

The need for maximum coverage and scale led to an Army request for a 12-in. lens of superior resolution for the K-18 camera. A low priority on an already overcrowded program permitted only exploratory calculations to be made at the Harvard laboratory. Computations made on the performance of the wide-angle Metrogon and Hasselkus lenses made prospects for improved performance at $f/4.5$ seem very poor indeed, in spite of the reduced angular coverage. No lens design was submitted by NDRC, although further work along these lines should be continued. In 1945, Bausch and Lomb delivered to the Army a 12-in. Metrogon redesigned for the smaller angular field. Consequently, the need of the Air Forces for wide-angle photographs of this scale was largely relieved.

24-in., $f/3.5$, 9x18 Lens for Night Photography[7h]

Exploratory calculations were made at Harvard on possible lens designs for the above specification. It seemed from the calculations and from consideration of the problem that secondary spectrum would prove to be a rather serious limiting factor in the performance. The use of a lens at night without filter and of such aperture serves to accentuate the secondary spectrum trouble, which reduces contrast and peak resolution. The 24-in., $f/3.5$, 9x18 lens was thought to crowd to the practical limit what can be accomplished with lenses not corrected for secondary spectrum, particularly for applications where suitable filters cannot be used. A discussion is given in OSRD Report No. 6028[7] on the effect of aperture and speed compromises in lenses for night photography, and the relationships to final resolution.

Calculations made during the course of the investigation led to the proposal of the apochromatic 100-in. lens design described earlier in this chapter. However, the speed of this apochromatic arrangement cannot be extended much beyond $f/8$, and would not suffice for night photography.

1.3.4 Wide-Field Designs of High Speed

A number of interesting designs are reported under Contract OEMsr-1078 by the Yerkes Observatory.[15] Although only a few might conceivably be used in aerial photography, it is important to bring these systems to the attention of those who are interested in very fast systems. There is insufficient space here to cover more than the underlying principles of these designs.

In May 1944, a paper was published by Maksutov[16] in which he describes the theory and presents computations of various lens-mirror systems making use of achromatic menisci to be used as correcting lenses for mirror arrangements. These menisci, in general, produce aplanatic, color-corrected mirror systems with speeds of the order of $f/1$ or slower, and fields of a moderate number of degrees, limited for practical purposes by curvature, and optically limited by astigmatism. In particular, one of Maksutov's systems made use of a meniscus with concentric surfaces, concentric also with a spherical mirror. Such a system operates equally well at all field angles. Its speed is limited only by considerations of zonal aberration, and longitudinal color.

Independently of Maksutov, the Yerkes workers developed a large variety of optical systems based on the fundamental idea of concentric surfaces. Such systems have the great virtue from the point of view of the designer that they require only axial ray-tracing and design; but they are necessarily always afflicted with curved field concentric around the same point.

The Yerkes report presents a large number of variations of this principle, including departures from symmetry, mostly for the purpose of color correction, both for all-air systems, and for air-glass systems. In the latter

case, the film rests against glass in the focal surface.

One of the most interesting of the systems is presented in Figure 39. This scheme can be used for high-speed wide-angle photography. It should be pointed out, however, that if curvature of field of the extent inherent in such systems (generally of radius equal to the focal

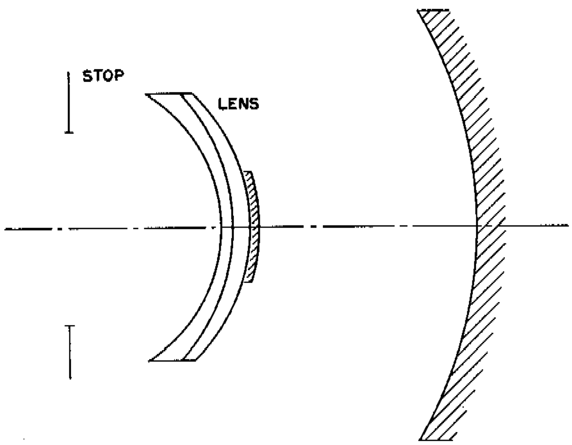

FIGURE 39. A concentric mirror-meniscus system.

length itself) be allowed for lens-type systems, the latter can compete on rather favorable terms at speeds of $f/1$ or slower. Therefore, it would seem expedient to recommend that mirror combinations be considered only where the speed exceeds $f/1$, and where the angular field does not exclude an important part of the aperture.

One of the most common troubles experienced with mirror systems is the blocking out of a considerable part of the light by the presence of a secondary mirror or by the photographic film. Very often, in the presence of residual aberrations, the important central peak of light (see discussions in the introduction, Section 1.1) is eliminated, leaving only the aberrations. It is evident that such systems cannot yield very sharp resolution. Consequently, it is important that in all systems where the central core of the image is blocked away, the residual aberrations be very small indeed. One cannot use effectively a blurred image with a hole in the center. Out-of-focus pictures are still more unsatisfactory.

1.4 LABORATORY TESTING

1.4.1 Introduction

The Mount Wilson Observatory (Contract OEMsr-101) and the Eastman Kodak Company (Contract OEMsr-392) carried out lens tests on both NDRC prototypes and other lenses of American and English manufacture, in the laboratory and in the air.

In addition, many laboratory and flight tests were carried out at Wright Field and again at Harvard (Contract OEMsr-474). Contact was maintained throughout World War II with other testing laboratories, such as the Royal Aircraft Establishment at Farnborough, England, and the National Research Council at Ottawa, Canada. Great benefits were derived from these several contacts, and particularly from Wright Field, where many years of experience prior to World War II opened the way for the extensive wartime testing there, and elsewhere.

The present section will limit discussion to laboratory testing as conducted under NDRC.

TABLE 4. Lens tests at Mount Wilson.

No.	Name	Focal length (in.)	Speed	Coverage	Maker
1.	Cooke Aviar	20	$f/5.6$	7x8	Taylor, Taylor and Hobson
2.	Ross survey	20	$f/6.3$	7x8	Ross
3.	Pentac	8	$f/2.9$	5x5	Dallmeyer
4.	Aero-Ektar	7	$f/2.5$	5x5	Eastman
5.	Aero-Ektar	24	$f/6.0$	9x18	Eastman
6.	Ross Astro	28	$f/7.0$	9x9	J. W. Fecker
7.	Plastic	8	$f/3.0$	5x5	T. S. Curtis
8.	Telestigmat	40	$f/8.0$	9x9	Bausch and Lomb
9.	Apochromat	36	$f/8.0$	9x9	Harvard
10.	Aerostigmat	12	$f/5.0$	9x9	Eastman
11.	Plastic	7.5	$f/2.8$	5x5	Polaroid
12.	Telestigmat, special	40	$f/8.0$	9x9	Bausch and Lomb
13.	Anastigmat	100	$f/10.0$	9x18	Harvard
14.	Wide-angle	5.95	$f/3.5$	120°	Harvard

Considerations of flight testing will be deferred to Chapter 2, except where laboratory testing attempts to duplicate the conditions in the air.

[redacted]

1.4.2 Testing at Mount Wilson Observatory[4b, 9b, 17, 18, 19]

During World War II the lenses listed in Table 4 were tested at Mount Wilson. The large range of focal lengths required that careful attention be given to details of the optical bench and auxiliary equipment.

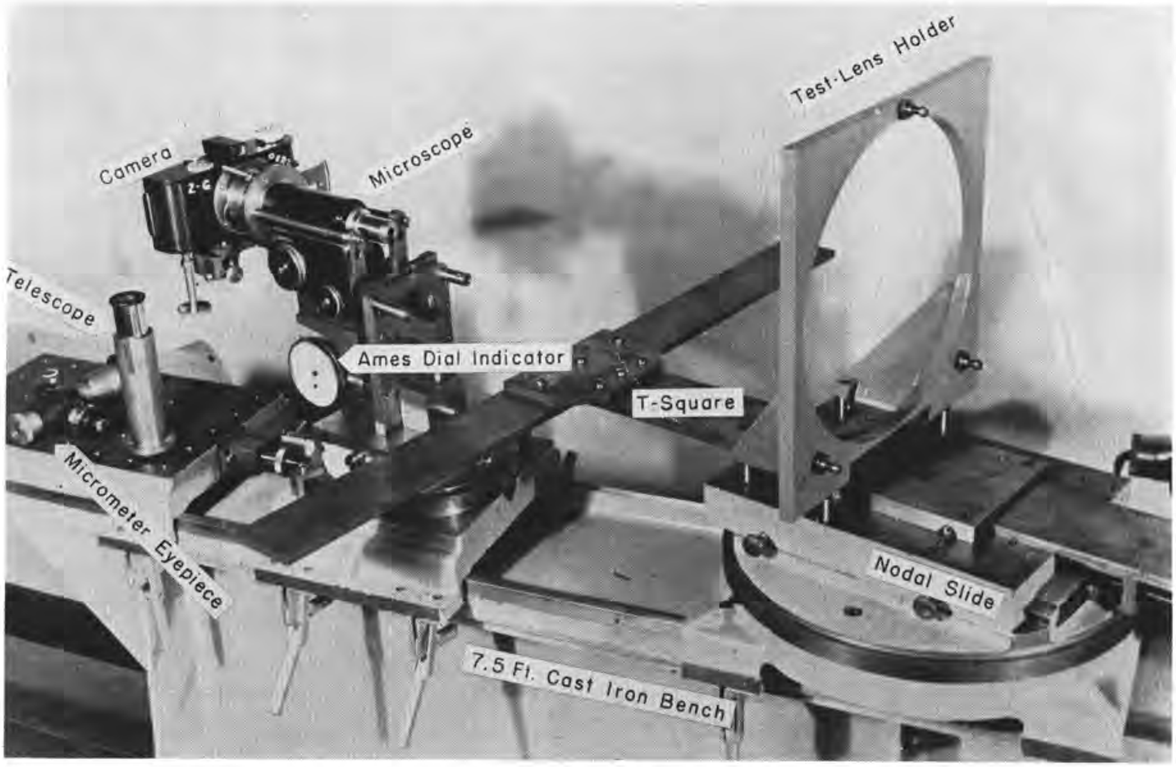

FIGURE 40. Principal parts of the Mount Wilson optical bench.

Test equipment at Mount Wilson consisted of a specially constructed optical bench shown in Figure 40. Lenses as large as the 100-in. $f/10$ anastigmat were accommodated on the nodal slide. Early in the testing program (lenses No. 1 to 7), the light source used was a small pinhole at a distance of 100 ft (No. 1 to 3) and 225 ft (No. 4 to 7), where the path was doubled by means of a large plane mirror. Illumination was provided by mercury arc, a headlight bulb, and a monochromator as needed.

For the later tests, a General Electric H6 high-pressure mercury lamp was added to the equipment for improving the illumination. The light distribution from this high-intensity lamp is that of a continuous spectrum with superposed mercury lines. With a yellow filter, the spectral distribution approximates that of sunlight through the same filter.

In order to provide for a uniformly illuminated slit in either vertical or horizontal direction, the following setup was made. Light proceeded vertically upwards from the capillary of the mercury lamp to a 45-degree mirror, and was there directed horizontally to the slit. Ordinary condenser lenses were used to form the image of the capillary on the slit. Rotation of the light source caused its image through the tilted mirror to rotate also. Thus, either a horizontal or a vertical slit could be used as needed. Finally, a rotating square prism was used for the purpose of moving the image of the light source back and forth on the slit to obtain uniform illumination.

Early in the Mount Wilson testing program, use was made of photomicrography for the determination of the image characteristics of the lens alone. Later, the testing procedures found

[redacted]

most informative were adopted and carried through systematically. Photomicrography was replaced by visual measures of resolution and by direct photography in the focal plane on both Super-XX and Microfile film.

TEST OF A 40-IN., $f/8$ BAUSCH AND LOMB TELEPHOTO LENS (IMPROVED PROTOTYPE)[4c]

The many lens tests made at Mount Wilson cannot all be fully described, but it is expedient to reproduce the results of a typical test. Figures 41 to 44 contain most of the pertinent information, and require only a few additional comments.

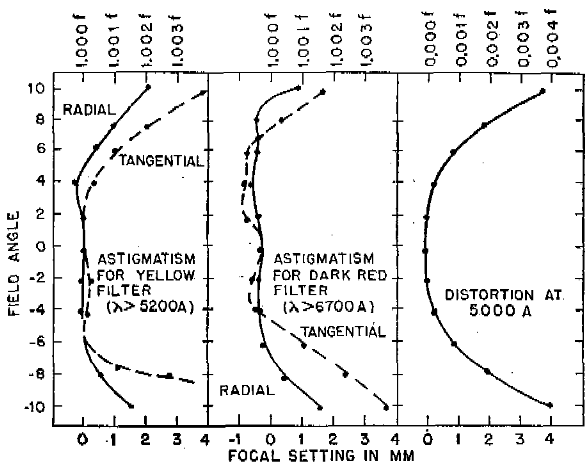

FIGURE 41. Astigmatism and distortion of Bausch and Lomb 40-in. telephoto lens (improved prototype).

The data on visual resolving power requires careful interpretation. Filter differences, and the phenomenal ability of the eye to distinguish resolution at low contrast can be very misleading. For example, if one sets up an ordinary condenser lens to form the image of a standard 3-line target, it is entirely possible to make readings of even 100 lines per mm, even though almost no light falls in the fine lines observed, and even though the chromatic and spherical aberrations are several millimeters in diameter.

It is probable that the more closely the lens approaches perfect correction, the more safely the visual observations can be used as a basis for evaluation. Visual measures are useful, but they provide only a necessary but not a sufficient condition. The designer cannot afford to have his judgment swayed by superlative visual resolution. Moreover, as described in the introduction (see Section 1.1), the best visual image is not identical with the best photographic image in regard to optimum distribution of light in the core of the image.

The testing results on the improved Bausch and Lomb $f/8$ telephoto lead to the following conclusions.

Astigmatism and Field Curvature. The results are shown in Figure 41. The asymmetry of the curves is due to imperfect internal collimation. The astigmatic images at large field

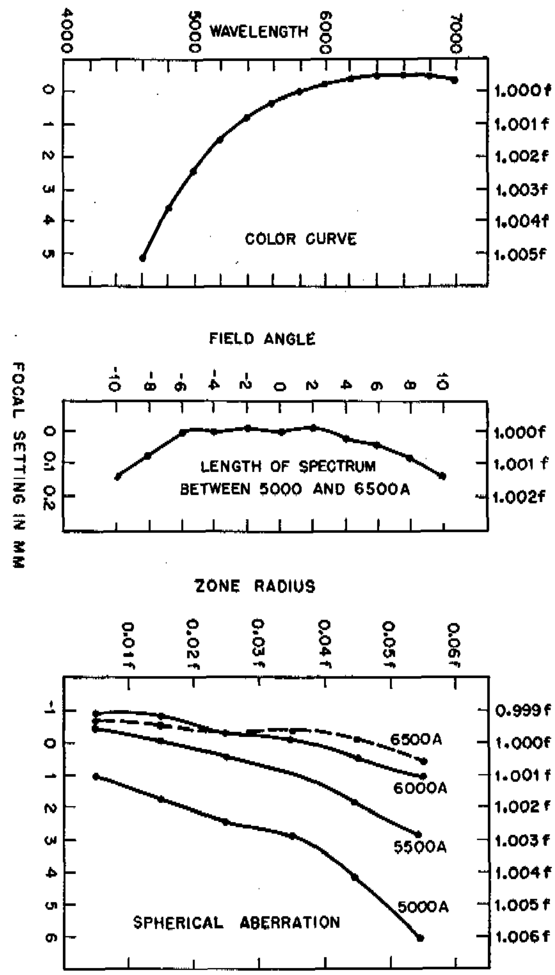

FIGURE 42. Color curve and spherical aberration of Bausch and Lomb 40-in. telephoto lens (improved prototype).

angles were very asymmetrical and the accuracy of the measures of the astigmatic foci was therefore comparatively low. Astigmatism and field curvature are relatively small up to about

[redacted]

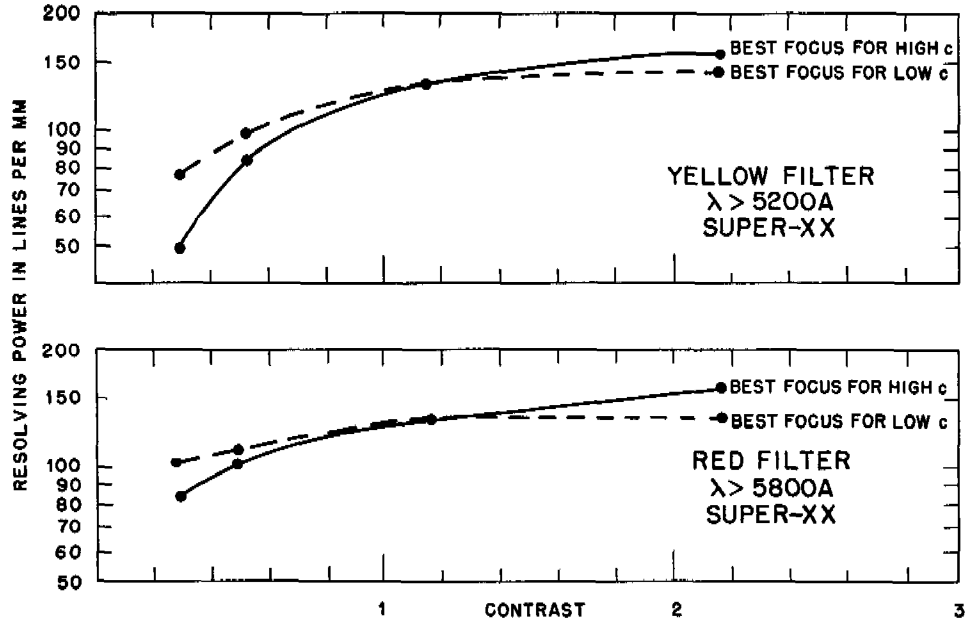

FIGURE 43. Visual resolving power versus contrast.

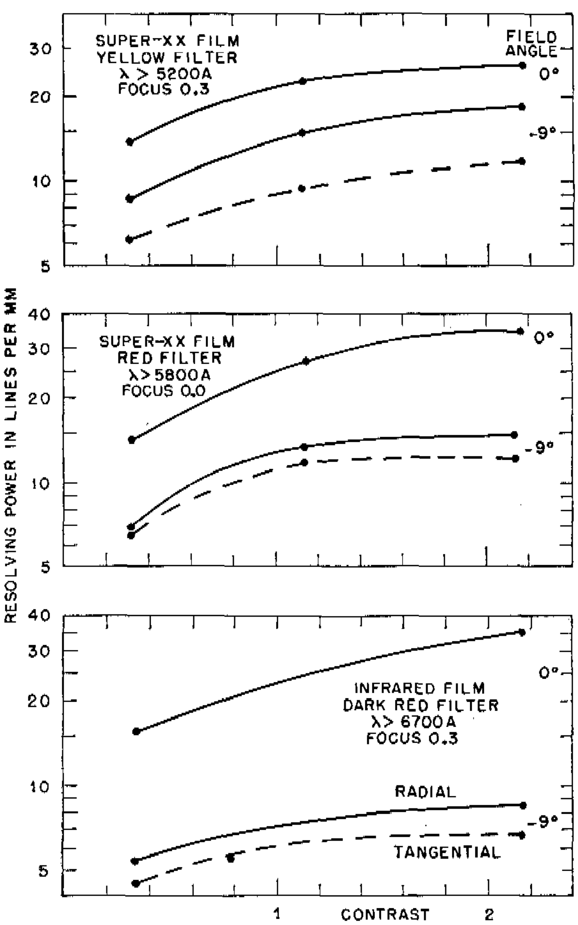

FIGURE 44. Photographic resolving power versus contrast.

5 degrees from the axis (3.5 in. from the center of the film). Their variation with wavelength between 5,000 and 6,700 A is not large. But the results of resolving-power tests with infrared film show that both astigmatism and field curvature increase very rapidly in the infrared region.

Distortion. The distortion (see Figure 41) has been measured with monochromatic light, since lateral chromatic aberration was noticeable. The distortion, which varies approximately with the third power of the field angle, is unusually large.

Chromatic Aberration. The color curve (see Figure 42) has its flat part at about 6,600 A. Obviously, the use of panchromatic film with a light red filter transmitting above 5,800 A is desirable, but the flat part of the color curve is at a wavelength somewhat longer than that which would give the best results even with this combination.

The chromatic difference of magnification is noticeable but not excessive. As a measure of the chromatic difference of magnification, the length of the spectrum between 5,000 and 6,500 A has been plotted in Figure 42, positive values indicating that the red image was at a larger distance from the center than the blue image.

Spherical Aberration. The spherical aberra-

[redacted]

tion (see Figure 42) shows considerable chromatic variation of a kind which suggests strongly the use of a light red filter. The spherical aberration seems to be smallest for wavelengths somewhat too far to the red for the use of panchromatic film.

Resolving Power. The targets were illuminated with tungsten "daylight" lamps. Visual resolving powers for the center of the field are shown in Figure 43. They were determined both with a yellow filter transmitting above 5,200 A and with a red filter transmitting above 5,800 A. There was a distinct difference between the best focal setting for high and low contrast; the focal setting for low contrast was smaller by 0.6 mm with the yellow filter and by 0.2 mm with the red filter. The results for each focal setting have therefore been plotted separately. As might be expected from the state of the chromatic corrections, the resolving power with red filter is better than with yellow filter.

Photographic resolving powers were determined on Super-XX 35 mm film with yellow filter and with red filter. Development was for 10 min in D-19 at 68 F. Since the color curve and the chromatic variation of the spherical aberration suggested good performance in the infrared, resolving powers were determined also on 35-mm Infrared Aero Panchromatic film (using the same development) with a dark red filter transmitting above 6,700 A. No focal difference between high and low contrast was found for the photographic resolving power. The results for high contrast (2.15) are plotted in the figures; the results for low contrast are somewhat less complete, some of the extrafocal settings at large field angles giving low resolving powers beyond the limit of the targets.

For the best focus in the center of the field, the dependence of resolving power on contrast and on field angle is shown in Figure 44. The best performance is obtained on Super-XX film with red filter. The resolving power with this combination for high-contrast targets in the center of the field is about 85 per cent of the theoretical maximum. The performance on infrared film in the center of the field is almost equally good, but the resolving power decreases rapidly with increasing distance from the center. The pronounced asymmetry of the curves for resolving power vs field angle, due to imperfect internal collimation, makes it difficult to assess properly the performance for larger field angles.

The objective is definitely much improved compared with the Bausch and Lomb Telestigmat $f/8$ tested earlier,[18a] and in a better state of collimation would probably be one of the best long focus objectives.

General Conclusions from the Mount Wilson Tests

The NDRC lenses proved to be on the whole an improvement over commercial types, partly because of a better color correction and partly because the lenses were designed for precision use. The improved commercial designs tested would, however, definitely take aerial pictures of high quality. It is believed that the NDRC lenses also represent a considerable improvement in the air from a practical point of view, since they are mounted in steel and are therefore relatively insensitive to thermal changes. The 36-in. fluorite apochromat was later thermostated in order to remove change of focus caused by the fluorite itself. The improvements achieved in the NDRC lenses were at the expense of more rigorous tolerances, and were unsuited to mass production. However, for precision reconnaissance these lenses are to be recommended.

It is believed that thorough tests of microscopic contrasts would show that the NDRC lenses are superior to most commercial lenses and, in accordance with the principles outlined in the introduction (see Section 1.1), would yield truer tonal values at all levels of exposure than most commercial lenses. The wartime experimental lenses manufactured by several companies represent also a definite improvement over the standard lenses.

1.4.3 Testing at the Eastman Kodak Company[20]

A very considerable number of laboratory tests were made at the Eastman Kodak Com-

[redacted]

pany under Contract OEMsr-392. Table 5 lists the lenses tested on a comparative basis.

The Eastman tests represent a lengthy controlled series employing the greatest range of variables yet attempted. In addition, composite results are presented by actual area of coverage instead of by field angle. Consequently, it is important to reproduce as much of the large volume of data here as feasible.

TABLE 5. Lens tests at Eastman Kodak Company.

No.	Name	Focal length (in.)	Speed	Coverage	Maker
1.	Wide-angle	5.95	$f/3.5$	120°	Harvard
2.	Plastic	7.5	$f/2.8$	5x5	Polaroid
3.	6-H-62	24.0	$f/6.0$	9x18	Eastman
4.	8-J-35	24.0	$f/8.0$	3x3	Eastman
5.	56-M-56	24.0	$f/5.6$	9x9	Eastman
6.	Apochromat	36.0	$f/8.0$	9x9	Harvard
7.	Wide-angle telephoto	36.0	$f/8.0$	9x18	Harvard
8.	8-T-87	36.0	$f/8.0$	9x18	Eastman
9.	Telephoto	40.0	$f/5.0$	9x9	Harvard
10.	Anastigmat	100.0	$f/10.0$	9x18	Harvard

IMAGE-ENERGY DISTRIBUTION MEASUREMENTS

This testing procedure is known as the wedge method for measuring the distribution of light across the image formed by a lens of a distant collimated line-source. As originated and used at Eastman, an illuminated slit 0.002 in. wide by 2 in. long is imaged with the lens under test at the object plane of a microscope. This image is in turn reimaged by the microscope on a colloidal carbon wedge, orientated with its slope parallel to the line image. Directly behind and in contact with this wedge is placed a fast negative panchromatic film. The wedge pattern so obtained is printed on Kodalith orthochromatic film and processed in a Kodalith developer for two minutes. The positive image is then printed on A-3 paper, which is processed in D-72 (2/1) for 45 sec. The contour of the wedge pattern is, then, a plot of log energy distribution against distance from the image measured along a line that is mutually perpendicular to the optical axis and to the line image.

Figures 45 to 55 reproduced from the Eastman report[20] show some of the energy-distribution patterns for the ten lenses, tested under a variety of circumstances. It is of interest to comment on unusual features of the tests.

The vertical scale is sufficiently constant between the many pictures to serve as a ready basis of comparison. The horizontal scale differs widely, however, so that the reader must judge the apparent linear sharpness on the basis of the image size scale at the bottom of each picture. Thus, the sharpest line of all is that given by the wide-angle $f/3.5$ lens of Figure 45. The apparent doubling of the tangential image in Figure 45 at large off-axis distances indicates that the lens is not in adjustment after its several trips across the country. Both Harvard and Mount Wilson results, as well as the nature of the design with its spherical symmetry, show a clean tangential image far off axis. A break in the cement at the center of the lens would not only explain the double image but also the low intensity of the image. When first assembled, there was no apparent difference in image quality in the radial direction anywhere over the 360-degree field.

The wedge patterns for the Polaroid 7-in. $f/2.8$ lens are enlarged (see Figure 46) by a factor of four as compared with the patterns for the standard Aero-Ektar. In photographic performance, overlooking the large difference in scale, the Polaroid plastic lens should give a photograph of the same order of quality as the widely used Aero-Ektar 24-in. lens, at least in the center of the field. The absence of sharp peaks in the images formed by both lenses in the outer parts of the field means reduced resolution.

Visual tests of the 36-in. $f/8$ apochromat indicated the presence of uncorrected violet in the nature of a tertiary spectrum rapidly increasing with the shorter wavelengths. Moreover, since the design makes use of only light crown glasses and fluorite, the lens is unusually transparent to ultraviolet light down to 3,500 A. It is not surprising, therefore, that Figure 50 shows a sharp central peak surrounded by considerable out-of-focus flare, since the heaviest filter used transmitted the near ultraviolet. Figure 51, showing the same test through a Wratten No. 12 filter, indicates that the apochromatic correction of the lens has been well achieved.

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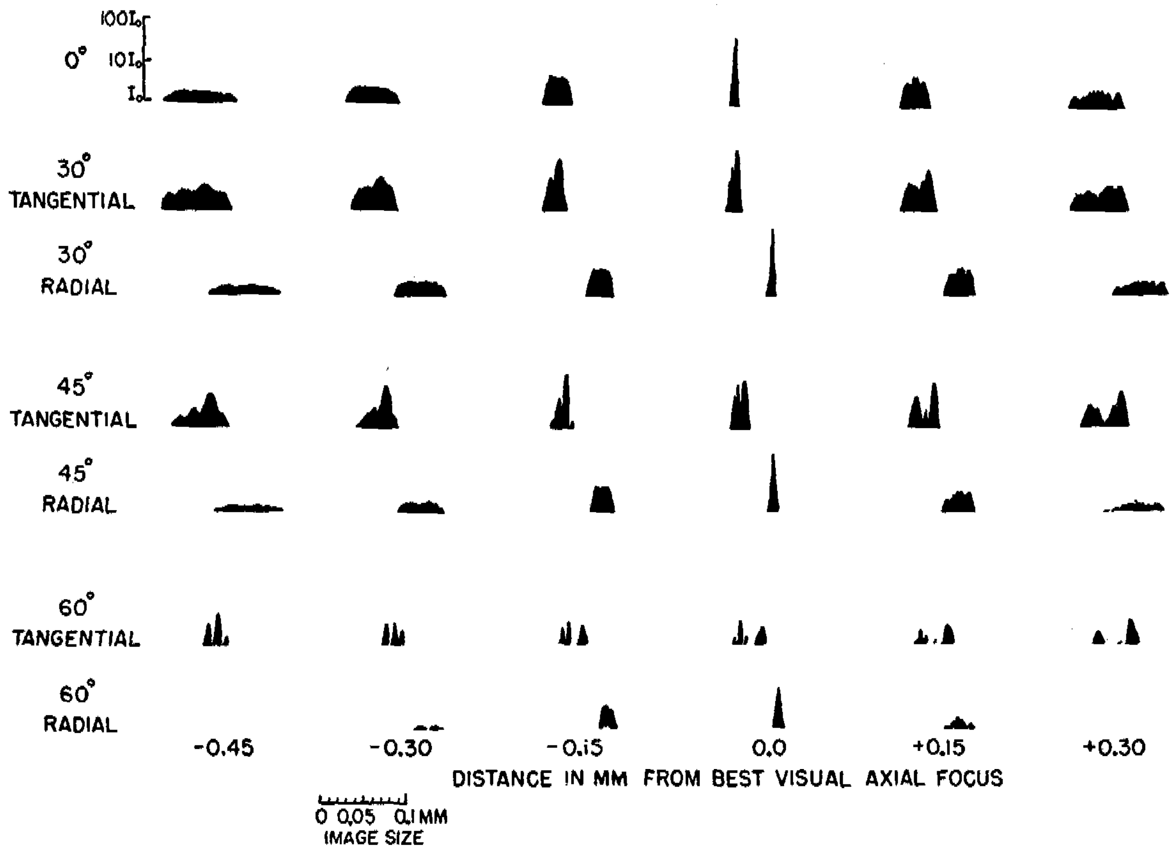

FIGURE 45. Harvard College Observatory 6-in. $f/3.5$ wide-angle lens.

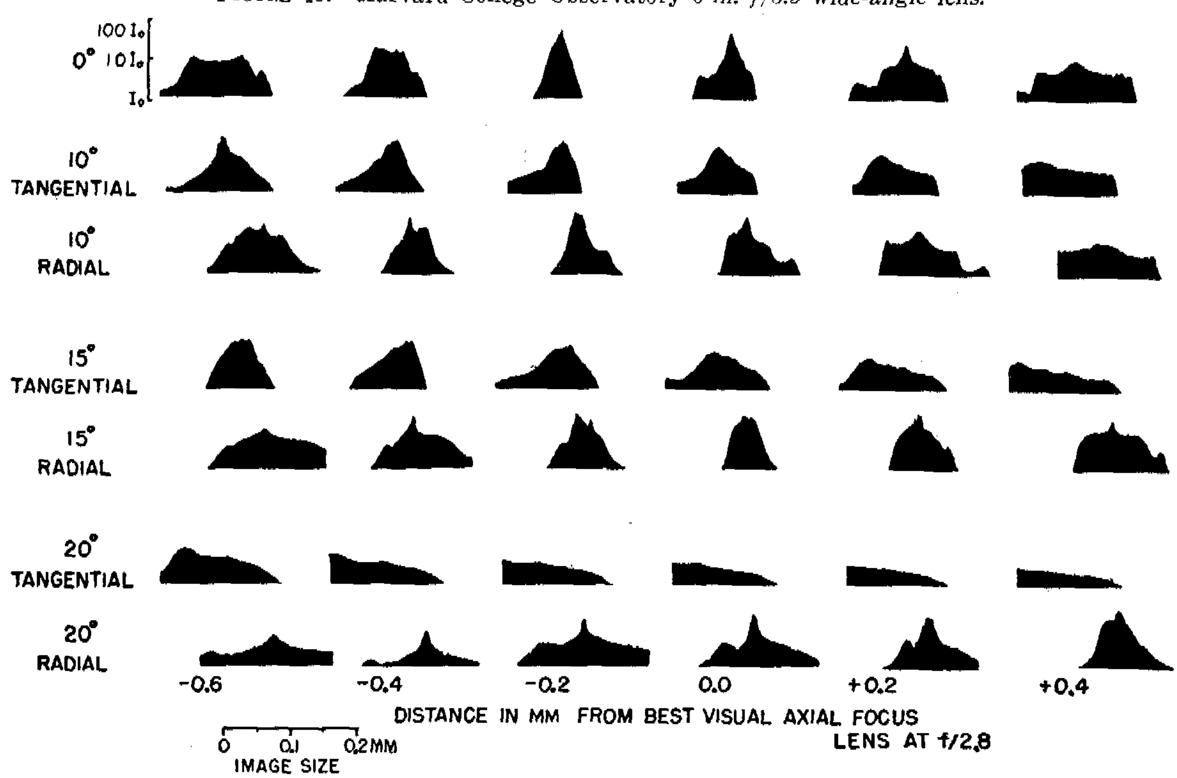

FIGURE 46. Polaroid 7-in. $f/2.8$ aerial camera lens.

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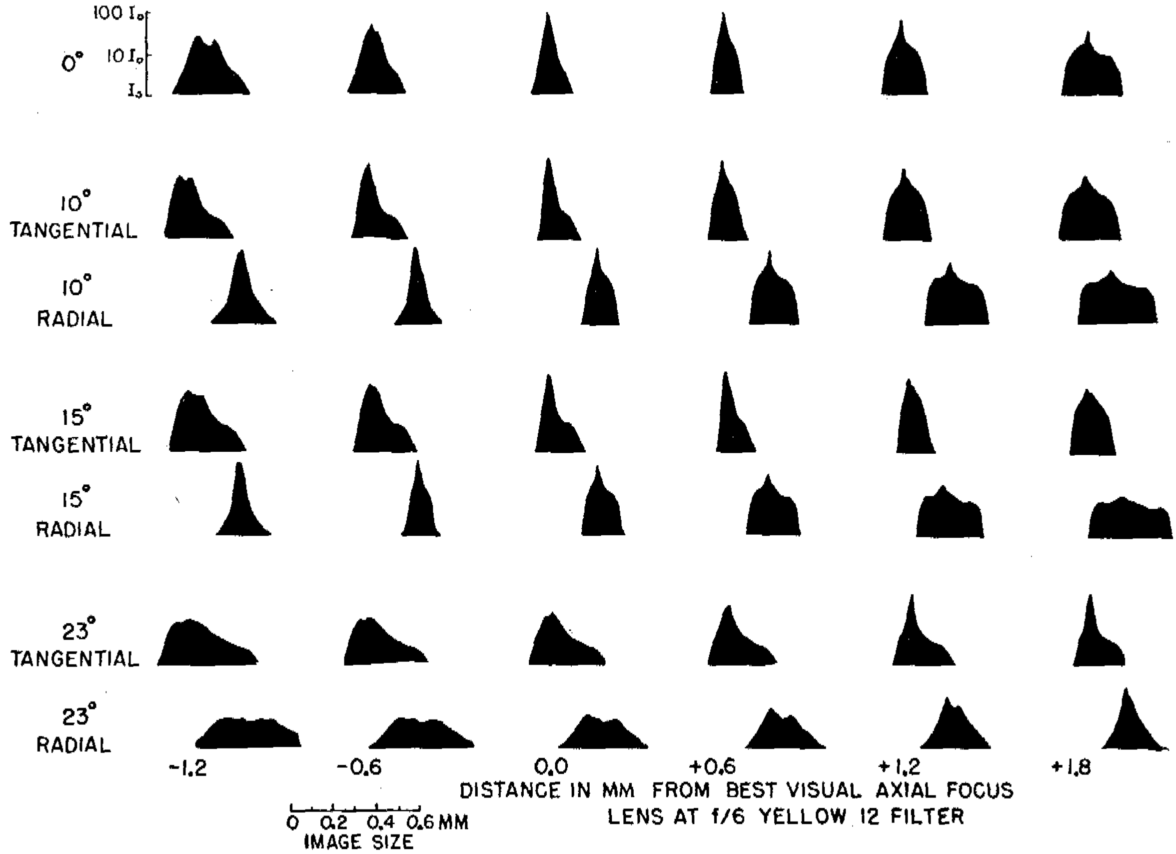

FIGURE 47. Kodak 24-in. $f/6$ Aero-Ektar EM-170 6-H-62.

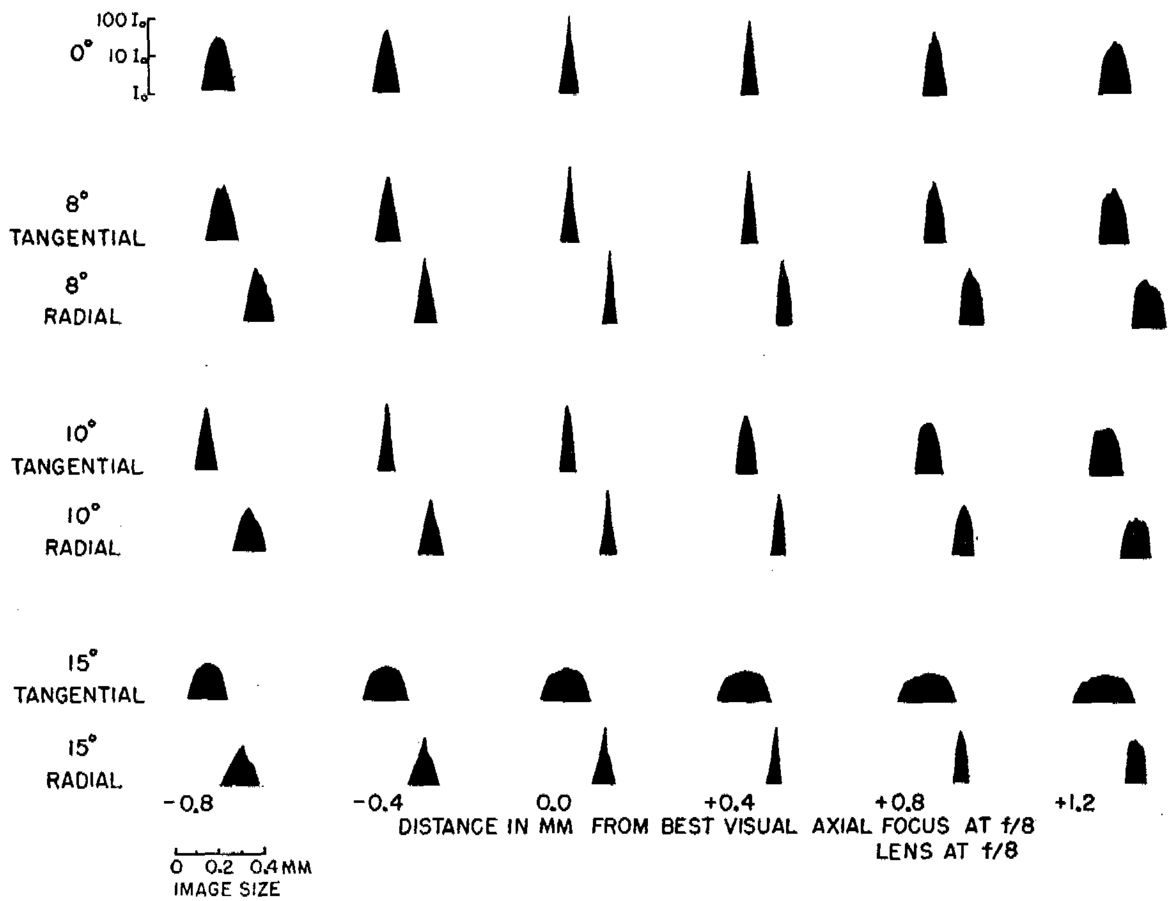

FIGURE 48. Kodak 24-in. $f/8$ aerostigmat formula 8-J-35.

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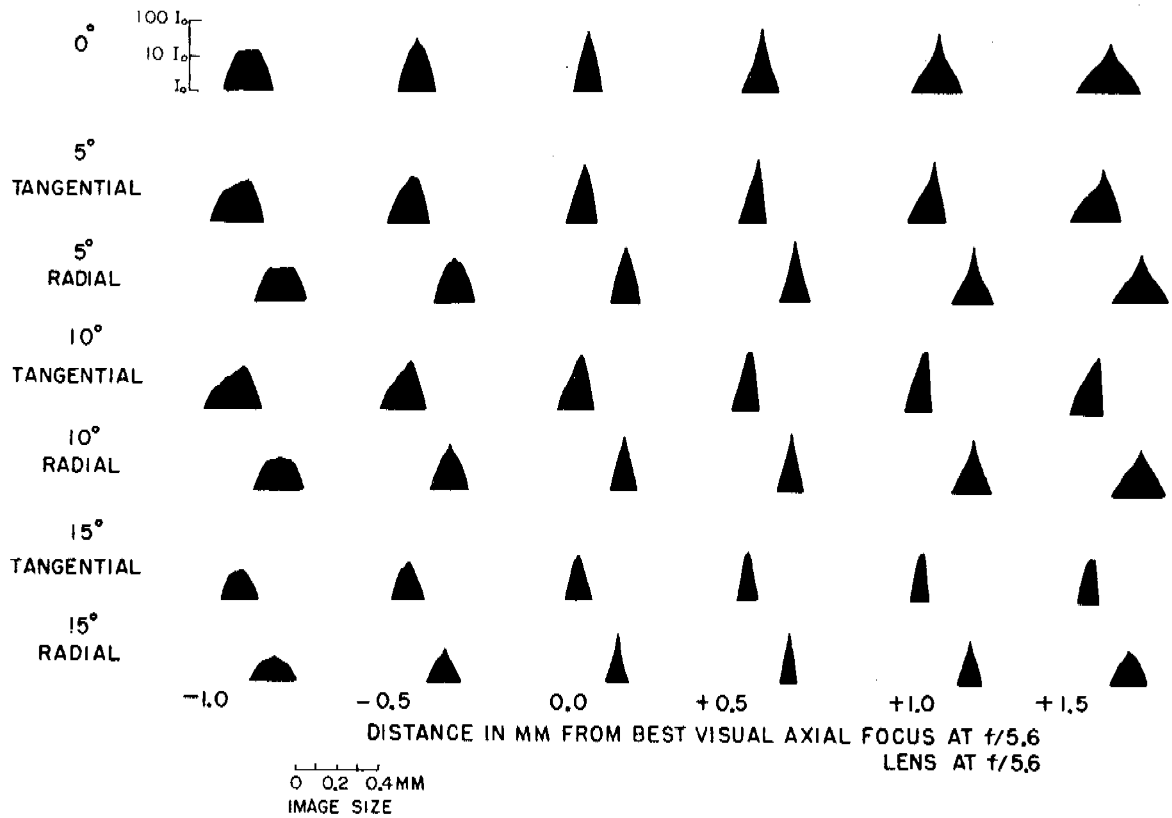

FIGURE 49. Kodak 24-in. $f/5.6$ Aero-Ektar formula 56-M-56. No. EE0001-3.

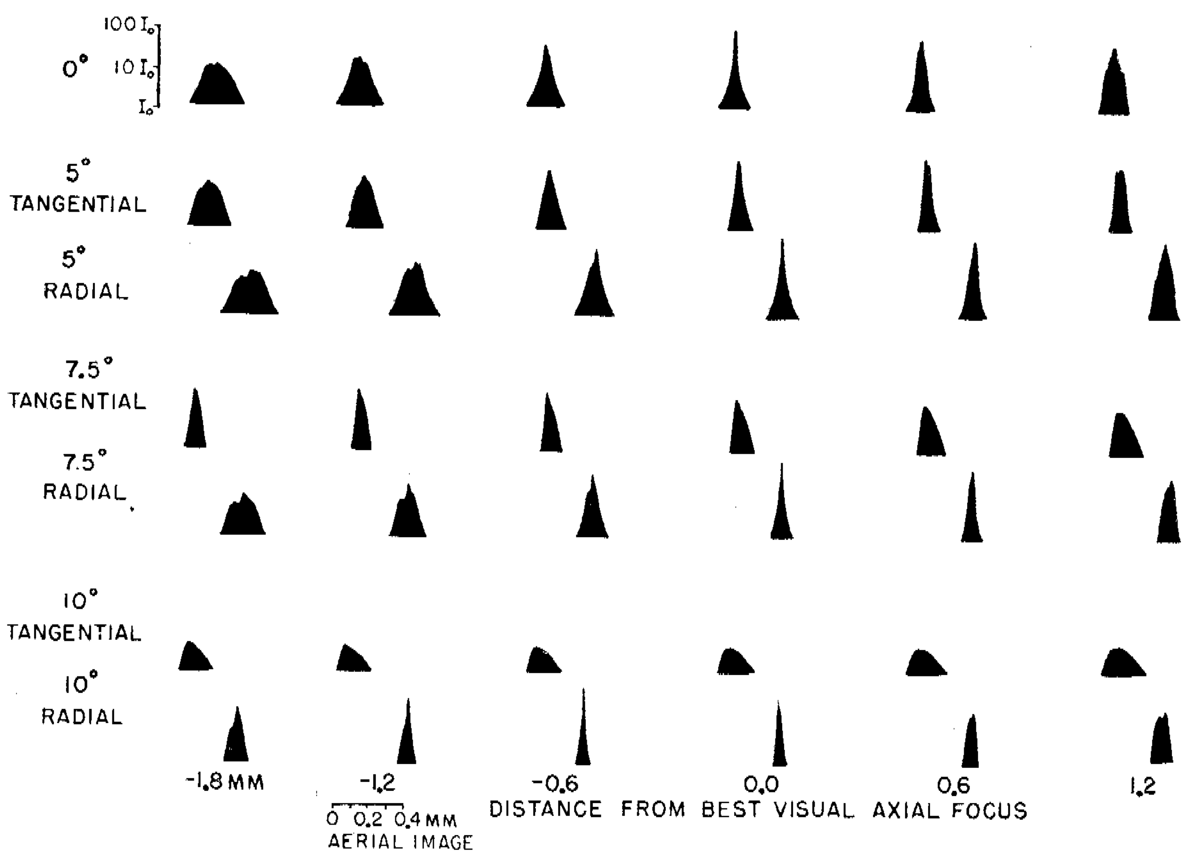

FIGURE 50. Harvard College Observatory 36-in. $f/8$ daylight lens F-3.

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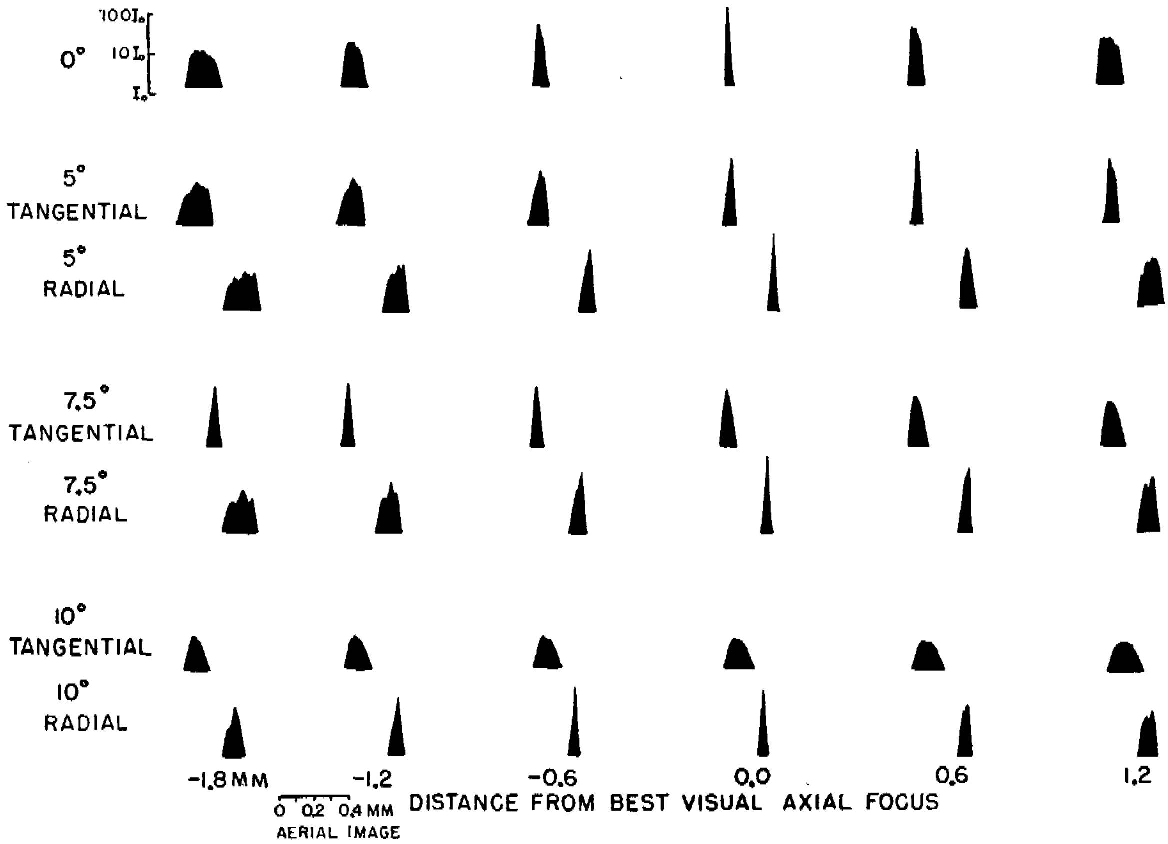

FIGURE 51. Harvard College Observatory 36-in. $f/8$ daylight lens F-3 plus No. 12 Wratten filter.

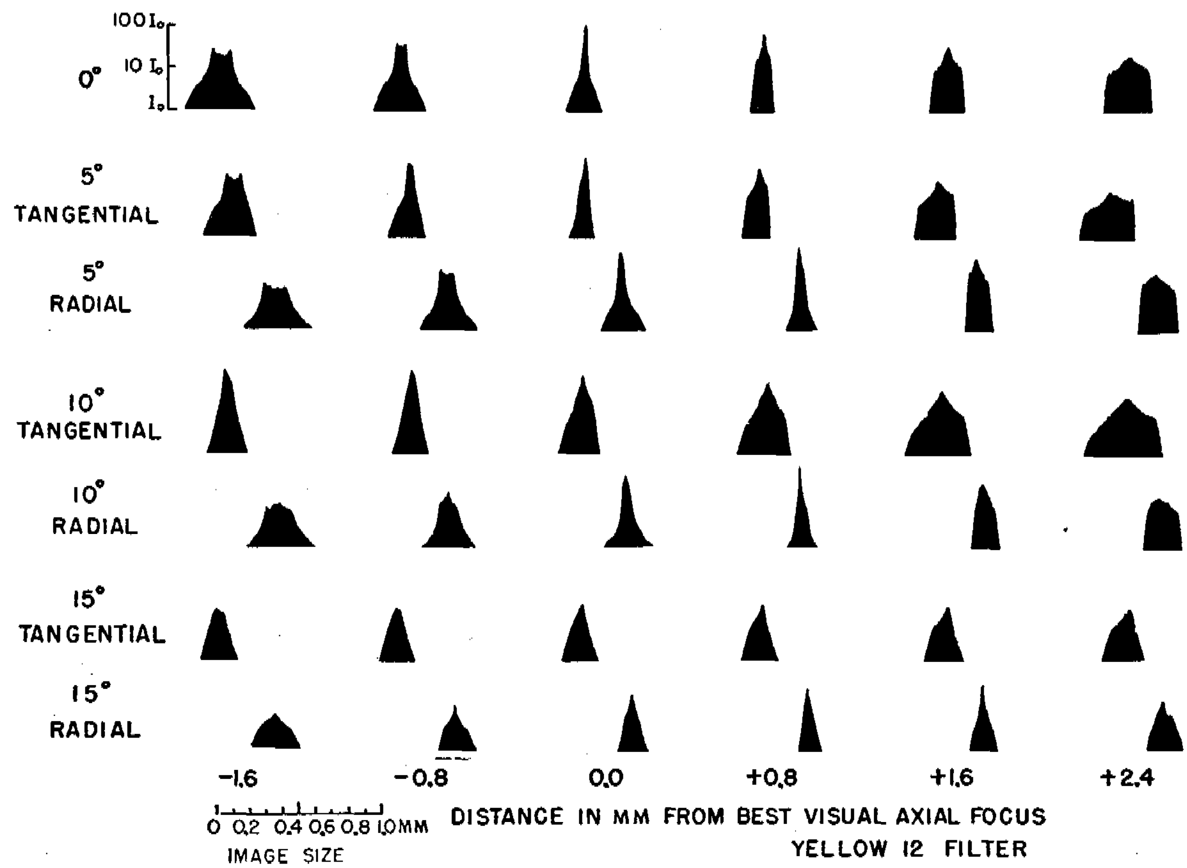

FIGURE 52. Harvard College Observatory 36-in. $f/8$ wide-angle telephoto lens ORL-T7-Y7-002.

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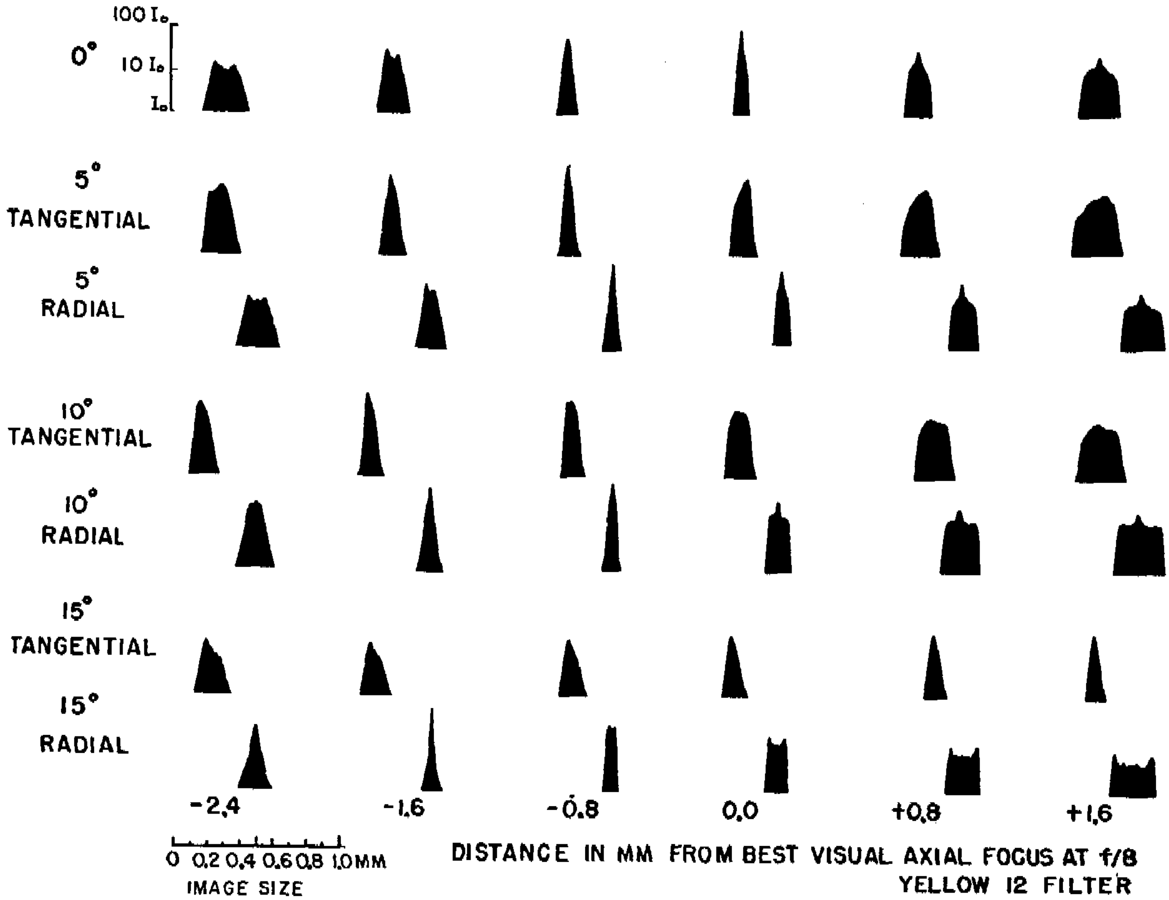

FIGURE 53. Kodak 36-in. $f/8$ telephoto ER0000 8-T-87.

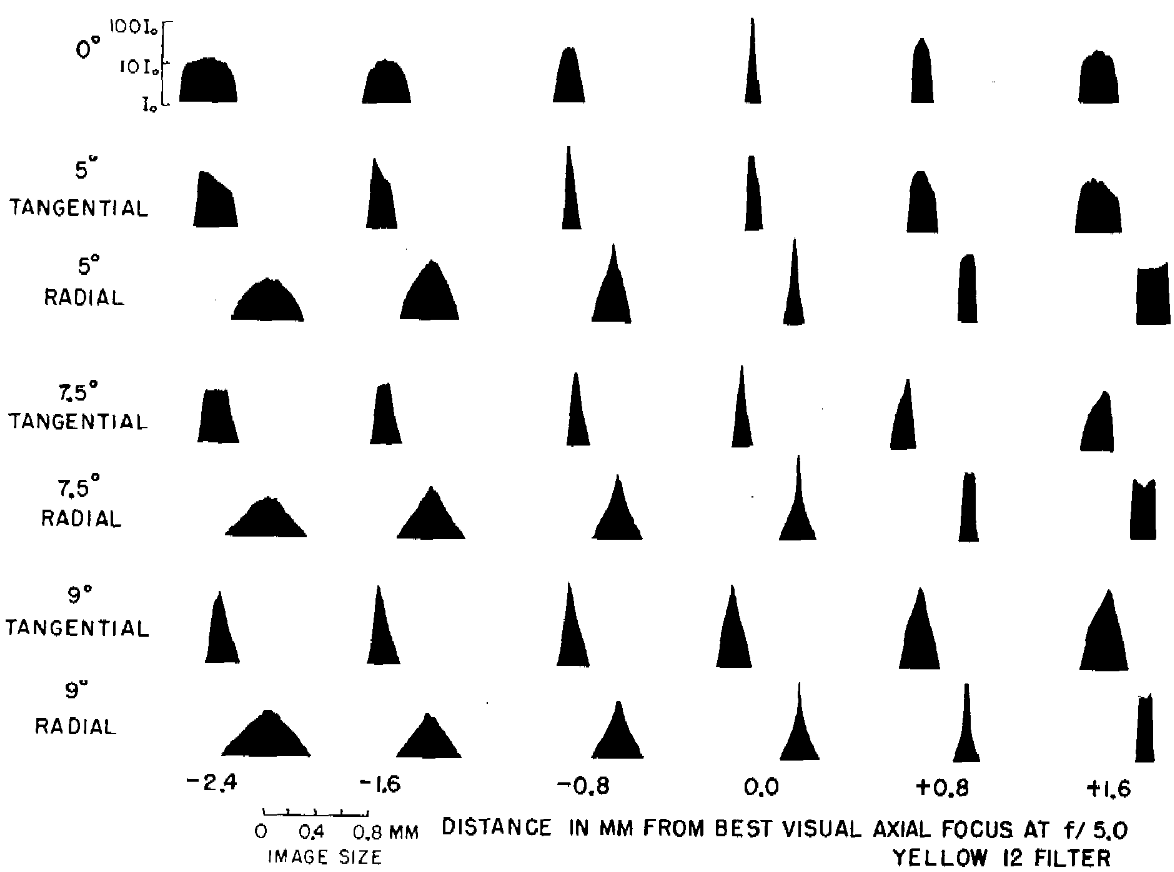

FIGURE 54. Harvard College Observatory 40-in. (1016 mm) $f/5$ distortionless telephoto Aero lens T5-Y7-113.

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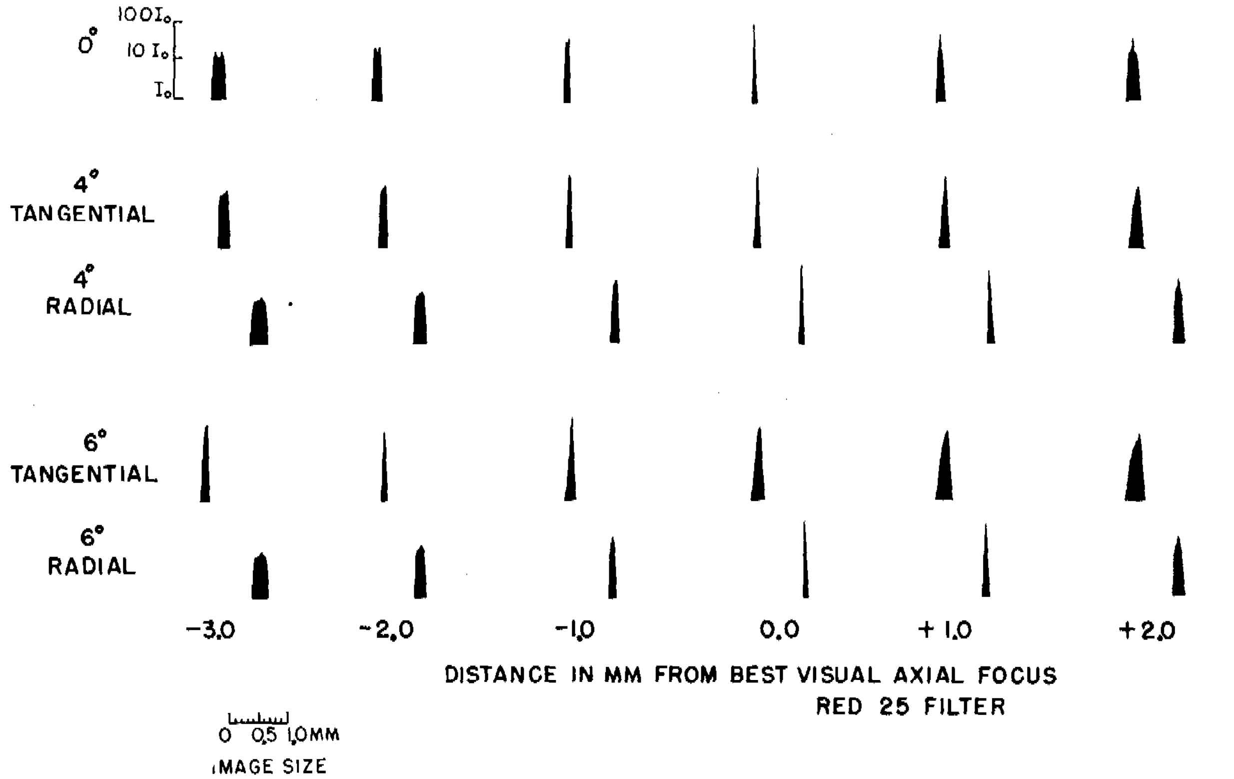


FIGURE 55. Harvard College Observatory 100-in. $f/10$ anastigmatic lens A1-R2-001.

The next NDRC lens, the 36-in. $f/8$ wide-angle telephoto for the K-18 camera, shows improvement in image quality of red over yellow filter. The improvement in tangential contrast in the red is due partly to the elimination of most of the secondary spectrum in lateral color rather than to reduced astigmatism. The lens design was based on sodium light. From experiments in laboratory adjustment of the lens, it is known that a slight alteration of curves would reduce the entire central 8-in. circle of the 9x18 picture to a much sharper image than shown and result in a general overall improvement. In the prototype a compromise had to be made on the central air space between spherical aberration and astigmatism far off axis. A slight redesign would materially improve the central image without affecting the optimum image quality far off axis.

The NDRC 40-in. $f/5$ telephoto also shows improvement between the yellow and red filters. Again the elimination of residual secondary spectrum in lateral color in green and deep red results in improved tangential contrast. The central peak in either test comes from the sharply focused light centered around sodium at 5,893 A.

It should be noted that the complexity of the 7-element 40-in. $f/5$ resulted in some variation in image characteristics between different lenses. The assembler was able to change air spaces over such a wide range that the image at any point could assume a variety of forms. Differences noted between production lenses involved centering flares, comatic residuals, and astigmatism near the edge of the field. In almost every case the image possessed a sharp central peak as required. It is believed that the tests shown here are of a typical production unit, assembled with greater care than is customary in the production run, but making no use of selected elements or mounting. The other lenses under test were less sensitive to production variations, owing to reduced aperture, focal length, and fewer elements.

The NDRC 100-in. $f/10$ lens, owing to the small lateral scale, shows less difference between yellow and red filter than would be supposed by a visual examination of the image. The design was based on red light for use with

an orange filter. The visual image showed a clear yellowish diffraction center, surrounded by the inevitably large green and blue out-of-focus flare due to secondary spectrum. The wedge tests emphasize again the importance of a central peak of resolution and the tolerable presence of large amounts of secondary color.

It is believed that further wedge tests should include studies of 3-line patterns at several contrasts. Such photographs would reveal clearly the influence of the central peaks, the loss of contrast with the filling up of the lines, and the decrease in peak density with aberration, based on an absolute exposure level. In laboratory studies intended to aid the designer in further work, it would be informative to enlarge the test photographs to such a point that structural detail in the image can be ascertained in the vicinity of the central peak. It would also be desirable to replot the data for constant ordinate and abscissa to serve more readily for visual comparisons.

TABLE 6. Laboratory testing technique for measuring lens-film resolving power of aerial lenses.

1. Test objects	(A) 3-line transparency. Line length 5× line width. Space between lines equal to line width $\Delta D > 3.0$ log units (B) Same as (A) except $\Delta D = 0.20$ (C) Cobb-type 2-line transparency. Line length 3× line width. Space between lines equal to line width. $\Delta D = 0.18$. (Test object made by Kodak-Harrow.)
2. Variation in line spacing between test object charts	(A) 0.1 log unit, 26 per cent increase (C) 0.04 log unit, 10 per cent increase
3. Method of measuring test object ΔD	Measured diffuse (pot opal) density
4. Method of mounting test object	Test object placed over a diffuser of white leader stock
5. Method of illuminating test object	3,000 K lamp + filter as listed in Table 7
6. Distance from test object to lens	As listed in Table 7
7. Position on axis about which lens is rotated when field is explored	Lens nodal point
8. Method of maintaining focal plane perpendicular to optical axis	Exposure plane orientation controlled by tangent bar
9. Field size	As listed in Table 7
10. Relation between astigmatic field and resolving-power measurements	Tangential resolving power measured with tangential lines. Radial resolving power measured with radial lines
11. Photographic materials used	Super-XX Aero Pan
12. Development	8 min, D-19, 68 F
13. Contrast (γ)	1.6
14. Processing equipment	Sensitometric developing machine
15. Test film size	35 mm by 12 in.
16. Method of keeping film flat	Pressure pad forces film in contact with a flat plate containing a ¾-in. diameter hole
17. Test exposure used	Constant for all angles on Super-XX, Aero Pan
18. Exposure timing method	Pendulum-type focal plane shutter
19. Density values produced on test strips	Density giving resolving power maximum is produced at approx. 0.7 field radius ($D = 1.2$ for Super-XX resolving power maximum)
20. Resolving power criterion	Smallest chart at which lines are just resolved using optimum viewing conditions
21. Method of viewing test	Microscope equipped to give from 12.5× to 100× magnification
22. Method of making visual measurements	A microscope with axis parallel to axis of lens bench is used to examine the aerial image
23. Method of securing average resolving power	The harmonic mean of the radial and tangential resolving power values is secured. This is then averaged over an area of the same size and shape as the exposure plane of the camera in which the lens being tested is to be placed, consideration being given to the increase of picture area with angle.

[redacted]

Lens-Film Resolving-Power Measurements

The lens-film resolving-power measurements were made on an optical bench assembly, which consisted essentially of a nodal slide for holding the lens, a test object at distances up to 100 ft, a 22-in. diameter 30-ft focal length paraboloidal mirror for collimation where needed, and the usual auxiliary equipment of an optical bench.

Wherever the distant source was used, the distance and orientation of the test objects were varied in order to maintain flat field conditions off axis. Both high and low contrast 3-line patterns and Cobb charts were used. Table 6 shows the complete specifications of the various testing procedures.

From the ten lenses tested there is a wealth of data too voluminous for reproduction. For detailed study the reader is referred to OSRD Report No. 6127.[20] A typical series of tests is given in Figures 56 to 63 for the 40-in. $f/5$ telephoto lens and comparative data for Mount Wilson results are shown in Section 1.4.4.

Average Lens-Film Performance

In accord with various procedures already used in England and Canada for averaging the lens-film performance over the specified picture area, the Eastman data include special averages obtained by integration over the square or rectangular field used. Figures 64 to 76 reproduce comparative data for the ten lenses tested. The averages were obtained by numerical integration over the picture area of the increment of area weighted according to the resolving power.

The apparent forward curvature of the average focus for the 5.950-in. $f/3.5$ wide-angle lens shown in Figure 64 is without significance, since the field curvature of the emulsion is based on the field curvature of the lens. However, the discrepancy is equal to that between the 5.950-in. known radius of the focal surface as constructed, and the 6-in. radius indicated. The photographic shells are curved to a radius of 5.950 in., and the lens was known to have the proper back focus within 0.002 in.

Overall Conclusions

It is better that the reader study the original data of the Mount Wilson[1, 19] and Eastman[20] test results before forming his own conclusions. However, it is possible here to isolate several factors of interest.

The peak performance indicated by the Eastman data was given on axis by the $f/3.5$ wide-angle lens and amounted to nearly 70 lines per mm on Super-XX. Next in order of increasing f-number, among lenses showing sharp peak in the wedge pattern, was the 40-in. $f/5$ with red filter, which gave 40 lines per mm. At $f/8$ the same lens yielded about 50 lines per mm. The Eastman experimental lens, 8-J-35, designed for telescopic performance over a restricted field with 24-in. focus at $f/8$, gave 42 lines per mm peak performance, going up to about 50 lines per mm at $f/16$. The 36-in. $f/8$ apochromat yielded a peak of 43 lines per mm.

These figures indicate a slight dependence of peak resolution on f-number, involving therefore film resolution-Rayleigh limit data. It would appear that a perfect $f/3$ lens might resolve 75 lines per mm on Super-XX at high contrast, that a perfect $f/5$ lens might resolve 65, a perfect $f/8$ lens about 58, a perfect $f/16$ 50 lines per mm, etc., decreasing rapidly at lower speeds. There is no doubt some dependence on color region of the emulsion, but results are inconclusive in the test data, and the differences are small between yellow and red.

Table 7 presents the final results of the averaged Eastman data. At first sight the figures on mean resolution are disappointing. The standard 24-in. Aero-Ektar, whose wedge images are the coarsest of the longer focal length lenses tested, yields a resolution of 20 lines per mm on the average over the 9x18 picture area. The Eastman lens, 8-J-35, designed for peak performance at $f/8$ over a 10-degree half field, yields 31 lines per mm for an infinitely distant object, and 36 lines per mm for an object 36 focal lengths away. It is evident that a slight readjustment would bring the performance for an infinitely distant object up to 36 lines per mm. This, then, may be adopted as the expected peak from a lens with field and

[redacted]

aperture restricted to near the Rayleigh limit.

Since the lenses of large focal length intended for 9x9 or larger picture areas with apertures up to $f/5$ average about 30 lines per mm over the field, it is evident that when full design performance in the numerous cases is realized, considerable effort will be required for the design and production of lenses capable of performance, on the average, over the field of better than 30 lines per mm.

Is the difference between the easily obtained 20 lines per mm for the Aero-Ektar field average, with its accompanying large depth of focus and insensitive production tolerances, and the 30 lines per mm average to date of the best experimental aerial lenses worth while? Will it be possible in the future to design lenses whose average performance over still larger picture areas at greater speeds approaches the perfect lens-film figures of about 65 lines per mm mentioned above?

For a partial answer to these questions the reader is referred once more to the considerations on contrast and resolution outlined in the introduction (see Section 1.1). The curves in Figure 1 show only a slight initial loss of resolution for a large loss of contrast. This fact is consistent with the apparently small differences between the resolution figures over the picture area for lenses with excellent wedge patterns and those with coarse patterns. It must be determined in future tests whether the 50 per cent gain in resolution and considerations of overall tonal values, or true range of contrasts on a microscopic scale are of sufficient importance for the purposes of aerial reconnaissance to justify procurement of lenses of sharp images instead of those with poorer images which can be made more easily.

The range of values of the resolution figures obtained from the Cobb low-contrast chart indicates the insensitivity of this type of testing

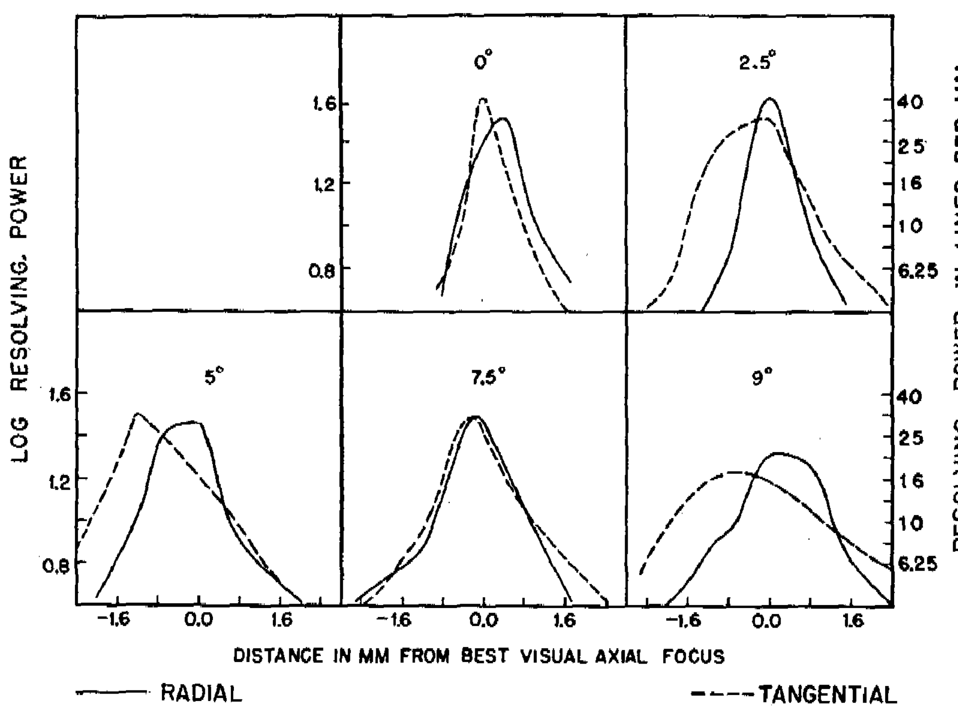


FIGURE 56. 40-in. $f/5$ telephoto at $f/5$, Super-XX Aero Pan tungsten + 12 filter, high-contrast 3-line test object.

[redacted]

TABLE 7

Lens	Aperture	Filter	Dimensions of Field	Distance from lens to test object	High-contrast 3-line test object: Log max. R.P.* lines/mm	High-contrast 3-line test object: Max. R.P. lines/mm	High-contrast 3-line test object: Max. avg. ang. resolution in seconds	Low-contrast test object: Type of low-contrast test object	Low-contrast test object: Log max. R.P. lines/mm	Low-contrast test object: Max. R.P. lines/mm	Low-contrast test object: Max. avg. ang. resolution in seconds
6-in. wide angle	$f/3.5$	red	60° half angle spherical	∞	1.69	49	28	Cobb	1.27	19	73
7.5-in. plastic	$f/2.8$	yellow	5x5″	"	1.25	18	61	"	0.67	4.7	230
7.5-in. plastic	$f/5$	"	"	"	1.31	20	53	"	0.98	9.5	110
6-H-62	$f/6$	12	9x18″	"	1.27	19	18	"	0.96	9.1	37
"	"	25	"	"	1.32	21	16	"	0.95	8.9	38
"	"	12	9x9″	"	1.37	23	14	"	1.00	10	34
"	"	25	"	"	1.37	23	14	"	0.99	9.8	34
"	$f/8$	12	9x18″	"	1.34	22	15	"	1.02	10	32
"	"	25	"	"	1.39	25	14	"	1.00	10	34
"	"	12	9x9″	"	1.40	25	13	"	1.07	12	29
"	"	25	"	"	1.43	27	12	"	1.05	11	30
8-J-35	"	12	10° half angle	"	1.49	31	11	"	1.14	14	24
"	"	12	10° half angle	36 F.L.†	1.56	36	9.3	3-line	1.24	17	20
"	$f/11$	12	10° half angle	"	1.61	41	8.3	"	1.25	18	19
"	$f/16$	12	10° half angle	"	1.56	36	9.3	"	1.26	18	19
56-M-56	$f/5.6$	12	9x9″	∞	1.43	27	12	Cobb	1.00	10	34
"	$f/8$	12	"	"	1.46	29	12	"	1.03	11	32
"	$f/5.6$	12	"	36 F.L.	1.42	26	13	3-line	1.14	14	24
"	$f/8$	12	"	"	1.46	29	12	"	1.16	15	22
"	$f/16$	12	"	"	1.55	35	10	"	1.24	17	20
36-in. Apochromat	$f/8$	daylight‡ daylight + 12	"	28.8 F.L.	1.33	21	11	Cobb	1.07	12	19
36-in. Apochromat	"	12	"	"	1.39	25	9.2	"	1.11	13	17
36-in. Telephoto	"	12	9x18″	∞	1.38	24	9.4	"	1.05	11	20
36-in. Telephoto	"	25	"	"	1.42	26	8.6	"	1.04	11	21
8-T-87	"	12	"	"	1.25	18	13	"	1.04	11	21
"	"	25	"	"	1.26	18	12	"	1.04	11	21
40-in.	$f/5$	12	9x9″	"	1.42	26	7.7	"	1.09	12	16
"	"	25	"	"	1.44	27	7.4	"	1.07	12	17
"	$f/8$	12	"	"	1.46	29	7.0	"	1.17	15	14
"	"	25	"	"	1.57	37	5.5	"	1.16	15	14
100-in.§	$f/10$	12	9x18″	"	1.45	28	2.9	"	1.09	12	7
"	"	25	"	"	1.43	27	3.0	"	1.10	13	6

* Resolving power, averaged over the field.
† Focal length.
‡ 3,000 K tungsten + 78AA filter.
§ Length/width of high-contrast test object 15/1.

[redacted]

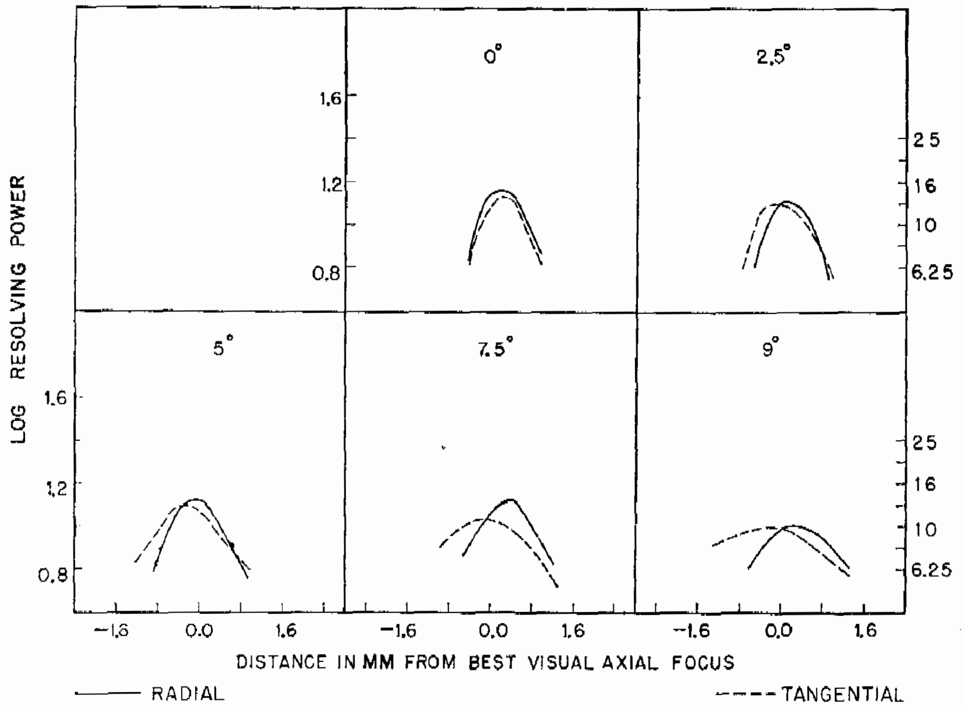


FIGURE 57. 40-in. $f/5$ telephoto at $f/5$, Super-XX Aero Pan tungsten + 12 filter, low-contrast Cobb test object.

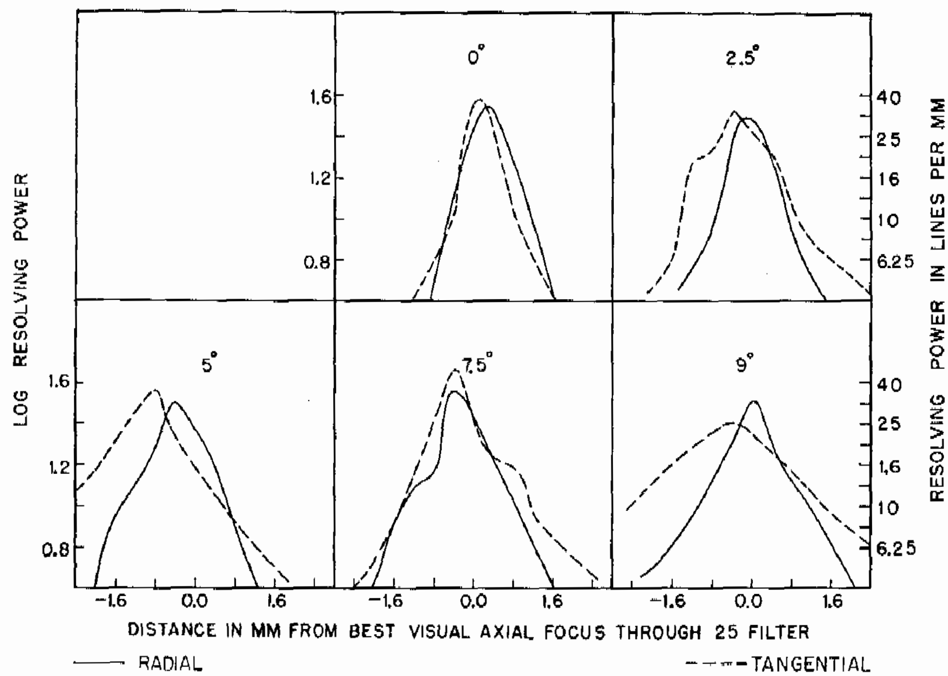


FIGURE 58. 40-in. $f/5$ telephoto at $f/5$, Super-XX Aero Pan tungsten + 25 filter, high-contrast 3-line test object.

[redacted]

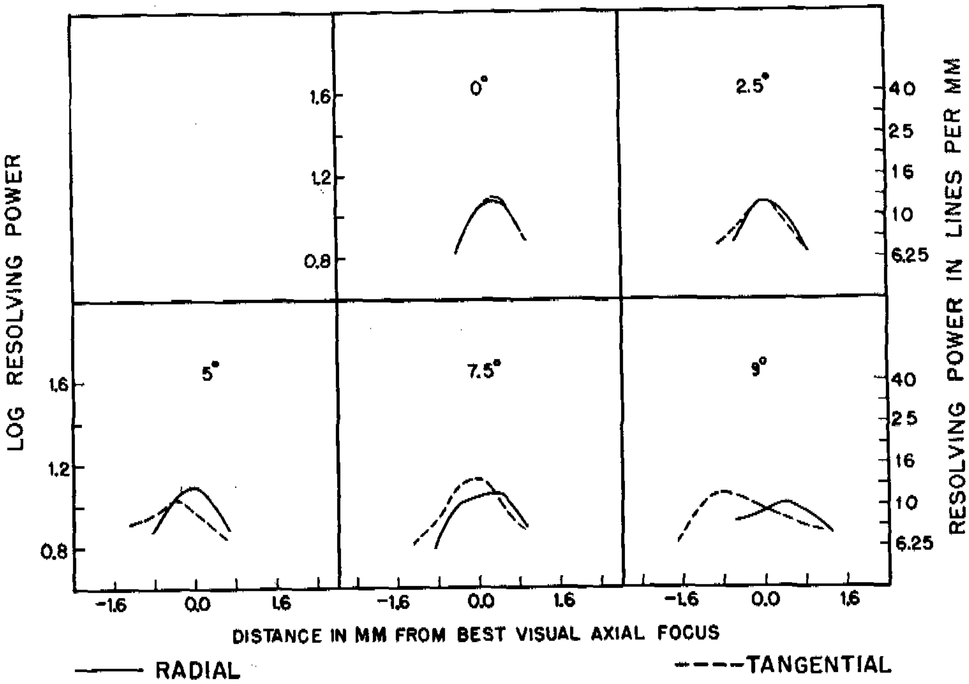


FIGURE 59. 40-in. $f/5$ telephoto at $f/5$, Super-XX Aero Pan tungsten + 12 filter, low-contrast Cobb test object.

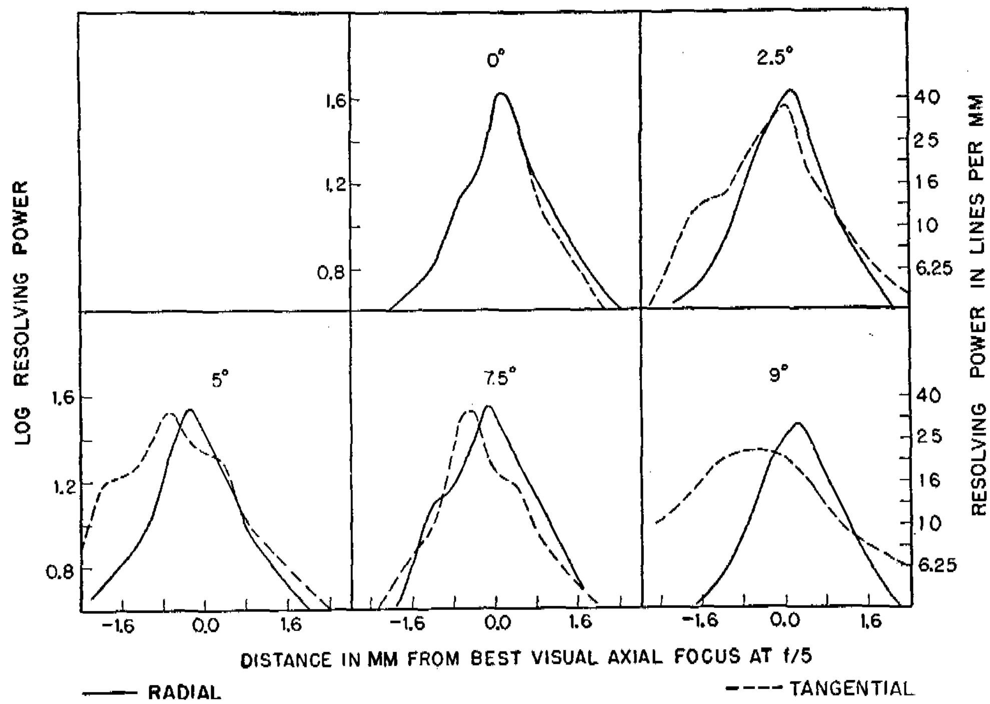


FIGURE 60. 40-in. $f/5$ telephoto at $f/8$, Super-XX Aero Pan tungsten + 12 filter, high-contrast 3-line test object.

[redacted]

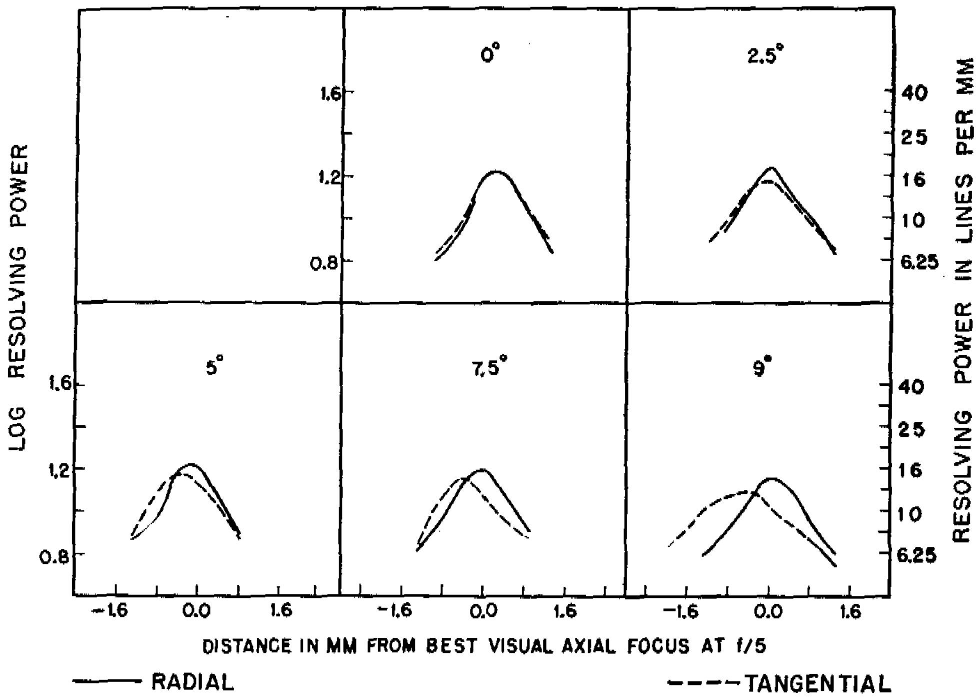


FIGURE 61. 40-in. $f/5$ telephoto at $f/8$, Super-XX Aero Pan tungsten + 12 filter, low-contrast Cobb test object.

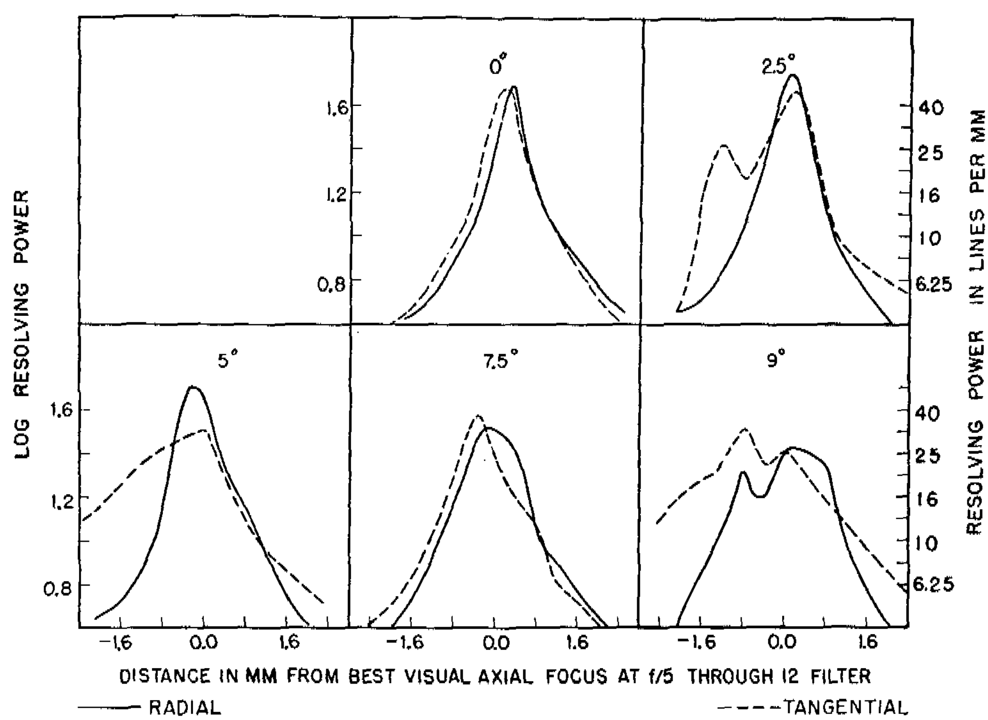


FIGURE 62. 40-in. $f/5$ telephoto at $f/8$, Super-XX Aero Pan tungsten + 25 filter, high-contrast 3-line test object.

[redacted]

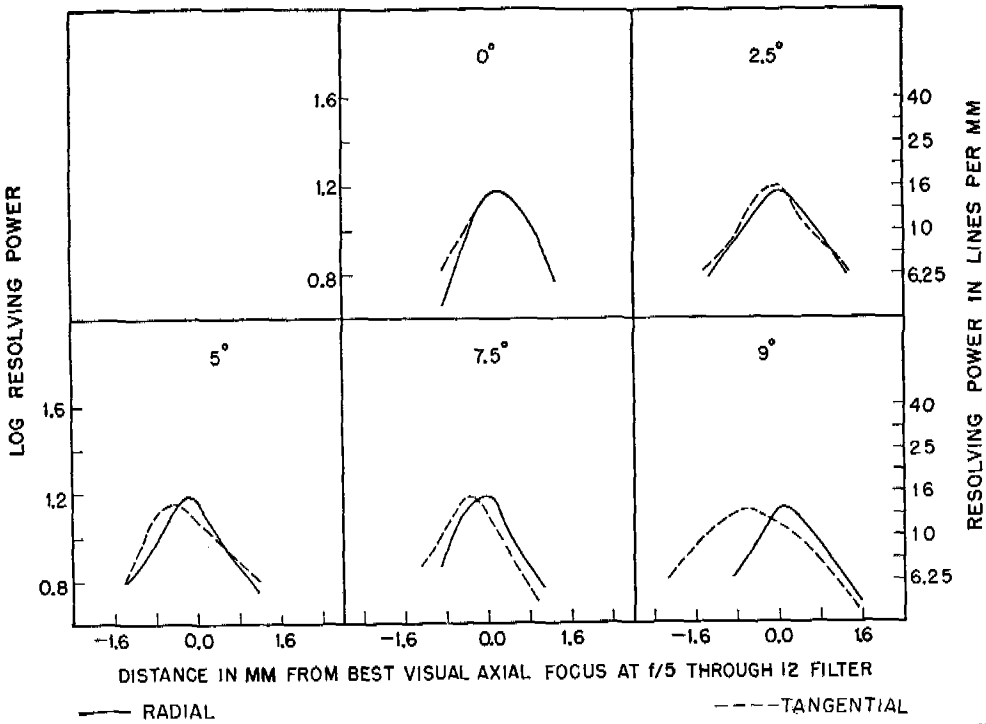


FIGURE 63. 40-in. $f/5$ telephoto at $f/8$, Super-XX Aero Pan tungsten + 25 filter, low-contrast Cobb test object.

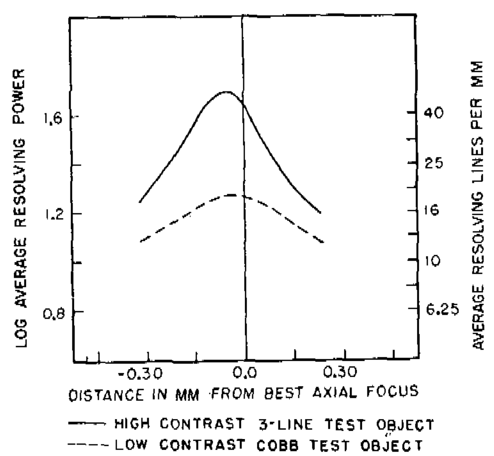


FIGURE 64. 6-in. $f/3$ wide-angle lens, Super-XX Aero Pan tungsten + red filter, average resolving-power. Over 60° half angle field on spherical exposure surface.

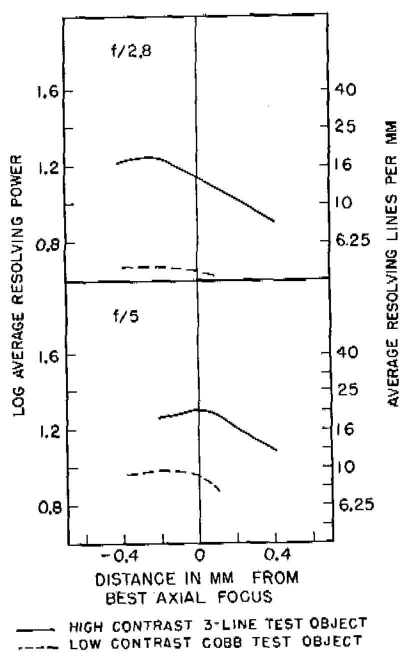


FIGURE 65. 7.5-in. $f/2.8$ plastic lens, Super-XX Aero Pan + yellow filter.

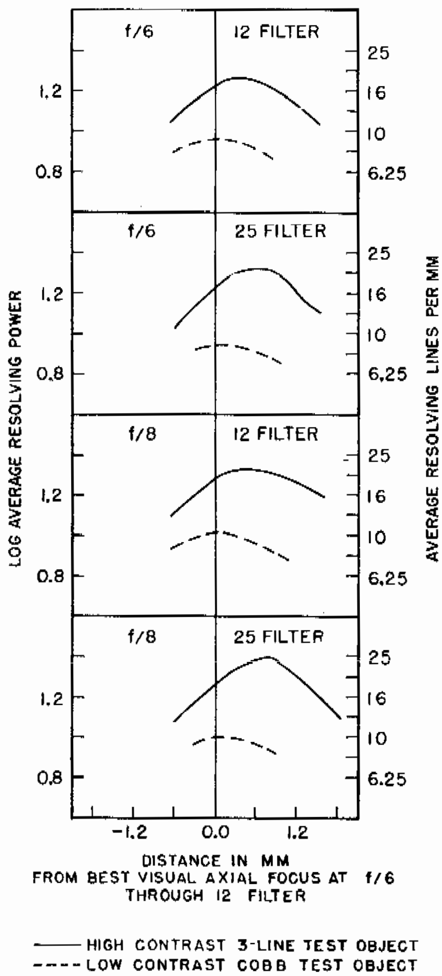


FIGURE 66. 6-H-62 EM170, Super-XX Aero Pan, average resolving power for 9x18-in. picture.

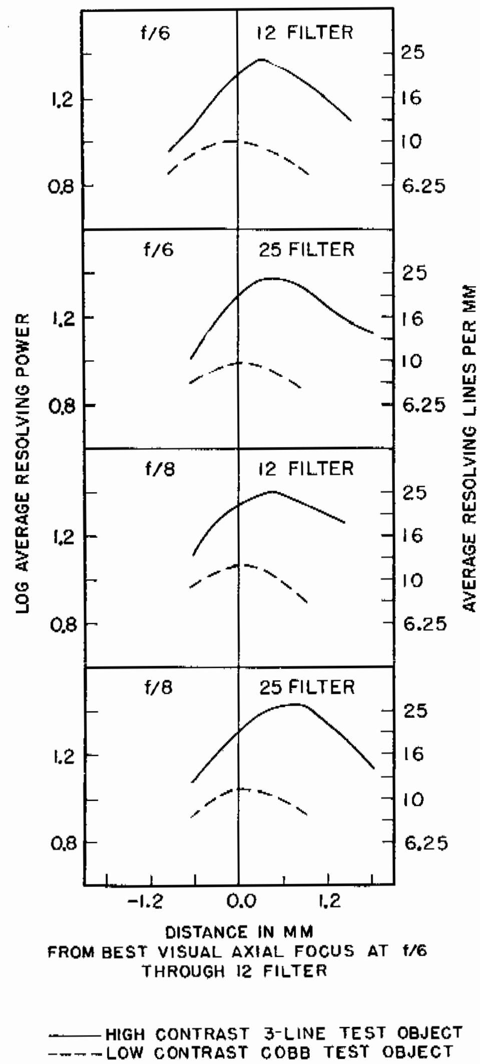


FIGURE 67. 6-H-62 EM170, Super-XX Aero Pan, average resolving power for 9x9-in. picture.

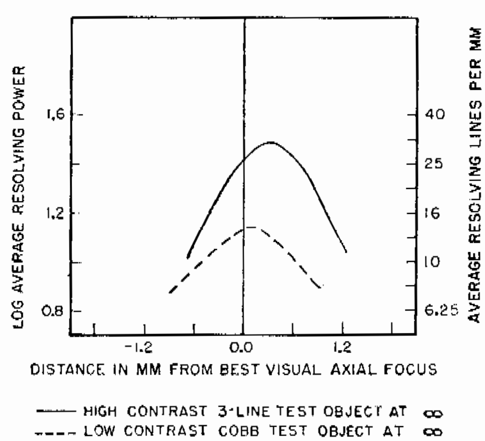


FIGURE 68. 8-J-35 at $f/8$, Super-XX Aero Pan tungsten + 12 filter, average resolving power 10° half field.

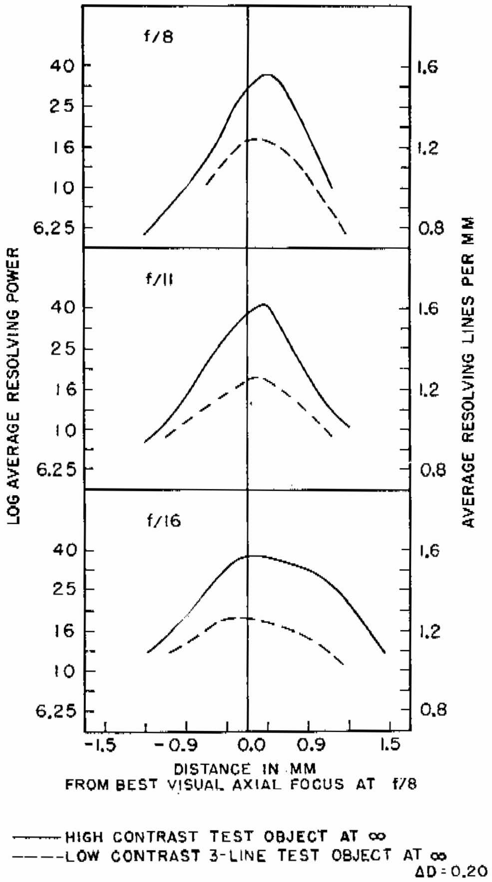


FIGURE 69. 24-in. $f/8$ aerostigmat formula 8-J-35, Super-XX Aero Pan tungsten + 12 filter, average resolving power 10° half field.

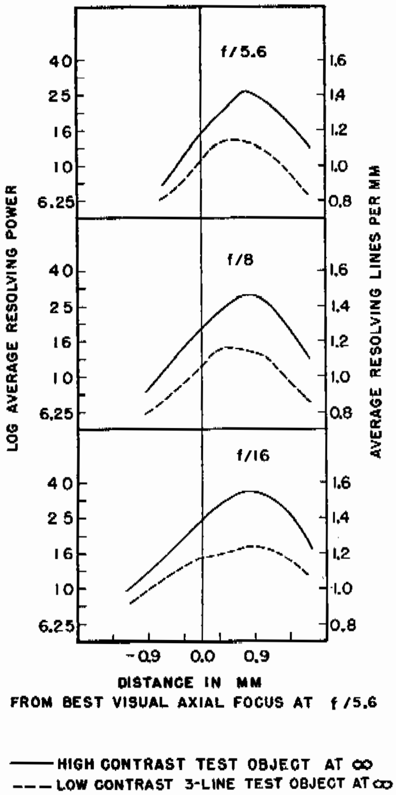


FIGURE 71. Kodak 24-in. $f/5.6$ Aero-Ektar EE0001-3 formula 56-M-56, Super-XX Aero Pan tungsten + 12 filter, average resolving power for 9x9-in. picture.

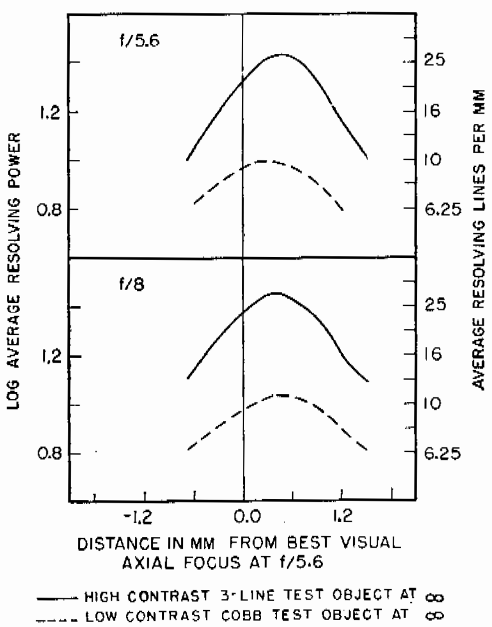


FIGURE 70. Kodak 24-in. $f/5.6$ Aero-Ektar EE0001-3 formula 56-M-56 Super-XX Aero Pan tungsten + 12 filter, average resolving power for 9x9-in. picture.

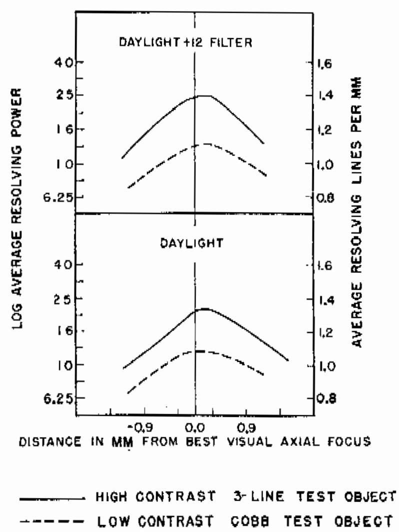
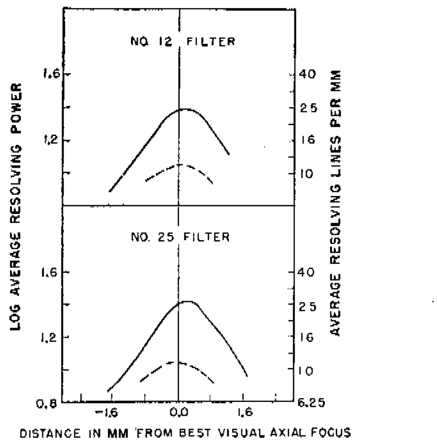


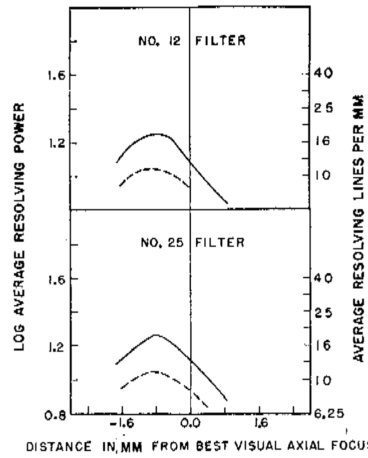
FIGURE 72. Harvard College Observatory 36-in. $f/8$ aerial apochromat, F-3, Super-XX Aero Pan.

[redacted]



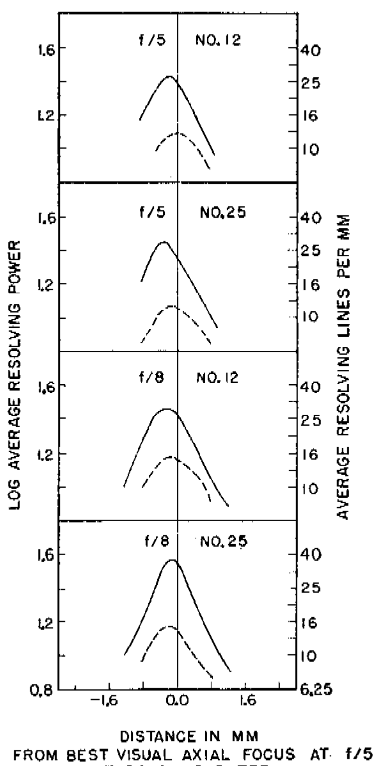
——— HIGH CONTRAST 3-LINE TEST OBJECT
----- LOW CONTRAST COBB TEST OBJECT

FIGURE 73. Harvard College Observatory 36-in. *f*/8 wide-angle telephoto, Super-XX Aero Pan, average resolving power for 9x18-in. picture.



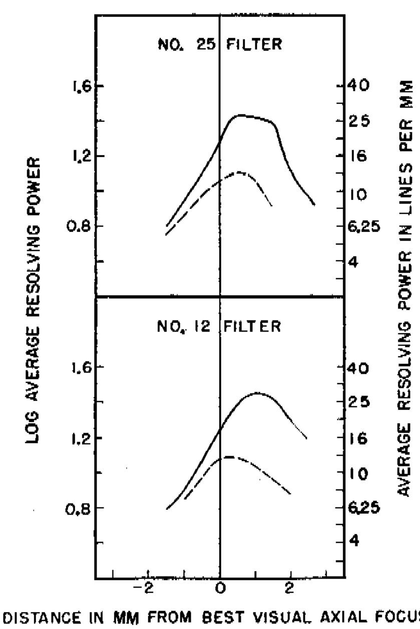
——— HIGH CONTRAST-3 LINE TEST OBJECT
----- LOW CONTRAST COBB TEST OBJECT

FIGURE 74. Kodak 36-in. *f*/8 telephoto 8-T-87, Super-XX Aero Pan, average resolving power for 9x18-in. picture.



——— HIGH CONTRAST 3-LINE TEST OBJECT
---- LOW CONTRAST COBB TEST OBJECT

FIGURE 75. 40-in. *f*/5 telephoto at *f*/5, Super-XX Aero Pan, average resolving power for 9x18-in. picture.



——HIGH CONTRAST 3-LINE TEST OBJECT
----LOW CONTRAST COBB TEST OBJECT

FIGURE 76. Harvard College Observatory 100-in. *f*/10 anastigmatic aero lens A1-R2-001, Super-XX Aero Pan, average resolving power for 9x18-in. picture.

[redacted]

for the isolation of lenses with sharp images, although the same figures may possibly emphasize the unsatisfying nature of aerial photography. In other words, it would be very difficult from studies of Cobb results alone to predict the appearance of the wedge patterns of good and bad lenses with any surety beyond what is known from general considerations.

Finally, the excellent angular resolutions obtained on the average for the lenses of large focal length reaffirms that an increase of focal length is of great importance for the final purpose of reconnaissance, that of greater ground resolution from a given altitude. Thus, in laboratory performance even the 100-in. focal length lens does not begin to exhaust the possibilities of angular resolution obtained by increase of focal length. It should be pointed out that the probable turbulence of the atmosphere is of the order of 1 sec of arc under aerial conditions, and that in the absence of movement or vibration, a focal length of even 250 in. in the air might be reached before picture sharpness would drop appreciably below 20 lines per mm in the absence of haze.

1.1.4 Comparison of Lens Tests at Mount Wilson Observatory and the Eastman Kodak Company

Three NDRC lens prototypes were tested at both Mount Wilson and the Eastman Kodak Company. For evidence on the reliability of such test programs, comparable data (see Figures 77 to 81) are reproduced from the respective reports[4, 20] for the 100-in. $f/10$ anastigmat. The resolution curves for tungsten plus Wratten No. 12 filter from the Eastman report are not included, since the design was based on use with an orange filter.

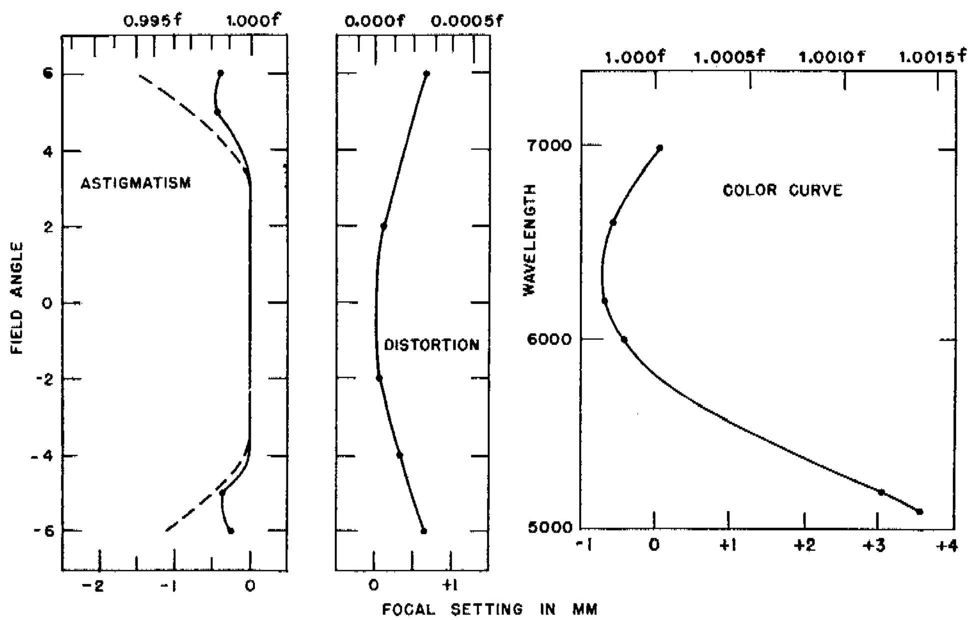


FIGURE 77. Astigmatism, distortion, and color curve of 100-in. $f/10$ anastigmat (Mount Wilson).

On axis, the peak Mount Wilson performance on Super-XX developed for 10 min in D-19 and 68 F is 29 lines per mm, whereas the Eastman results are more than 40 lines per mm under very comparable conditions. In general, the Eastman resolution figures are higher than those of Mount Wilson on the same test. Similar discrepancies occur in tests of the other lenses. (See Figures 8 and 64.)

The Mount Wilson results, in agreement with design data, indicate a very flat mean field

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(see Figure 79) at peak resolution, varying by 0.2 mm at most. The results of visual determination of field curvature indicate good symmetry on both sides of the optical axis, proving both good alignment of the elements and of

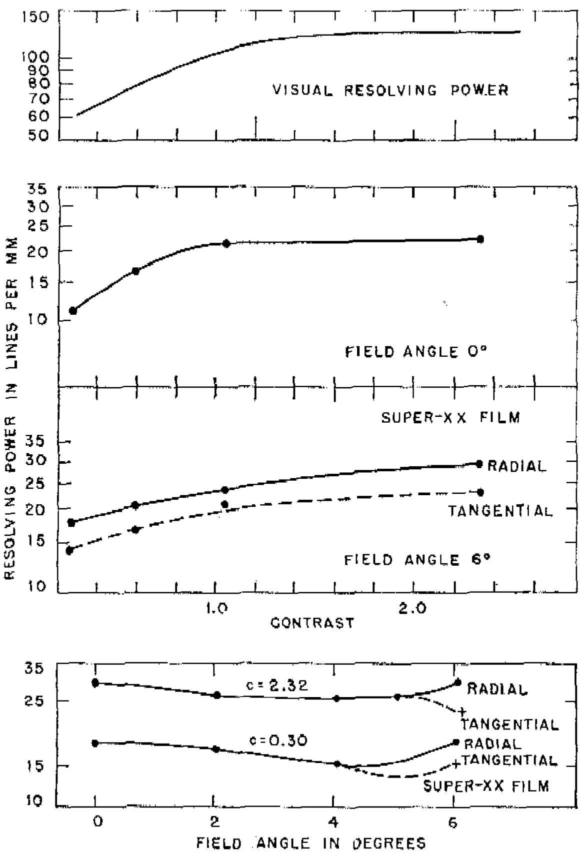

FIGURE 78. Resolution and contrast of 100-in. $f/10$ (Mount Wilson).

the testing equipment. The Eastman data show a backward curving field to the extent of almost 1.5 mm, based on measurements apparently confined to one side of the axis. The indicated discrepancy is small compared to the size of picture and camera, and illustrates the difficulty of large lens work.

It is obviously very dangerous to lump together testing results at separate laboratories until considerable standardization has been achieved. Each laboratory must work toward the utmost self-consistency of the procedures chosen, and check the precision of the testing equipment in all respects.

1.4.5 General Considerations Concerning Lens Tests

The complete laboratory lens test would include both visual and microphotometer measures of tangential and radial resolution at spaced focal settings at all parts of the picture area, making use of various targets, contrasts, absolute exposure levels, apertures, filters, and emulsions. In addition, studies would be made of the distribution of light in the image under all the above circumstances, employing both

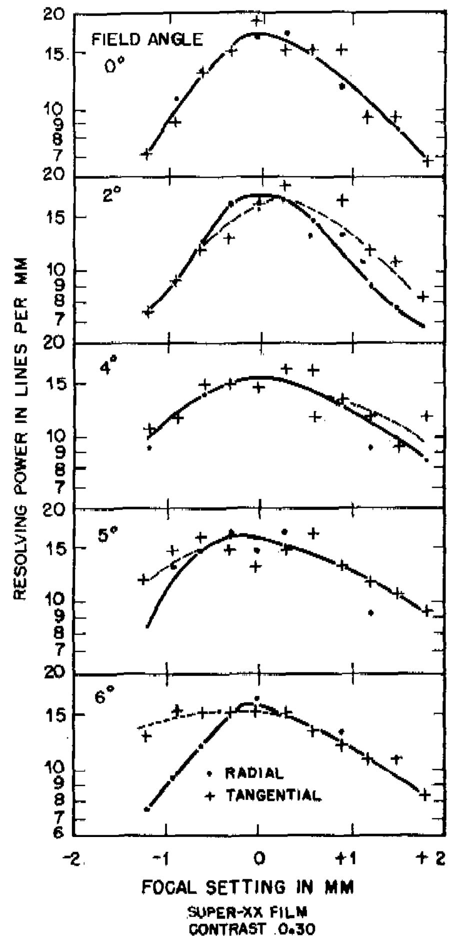

FIGURE 79. Resolving power versus focal setting for 100-in. lens (Mount Wilson).

photomicrography and the wedge method. In practice, some limitation on these numerous variables must obviously be imposed.

TYPE OF TARGETS

The investigation of the Royal Aircraft Establishment at Farnborough to determine

[redacted]

the reliability of different types of targets proved that either the Cobb 2-line test chart (see Figure 2) or the American 3-line chart are of the same order of certainty within the knowledge of what is being tested. The objective character of Canadian annuli (see Figure 2) is deserving of considerable attention. The same investigation established that the ratio of successive target sizes should be $\sqrt[6]{2}$, or sent ground objects of widely varying nature, it would appear that present types of testing targets in the various laboratories may as well be retained.

Each research worker should realize that his own test methods will ultimately produce optimum results on ground targets most nearly like his own targets, and should discount the absolute importance of improving results already

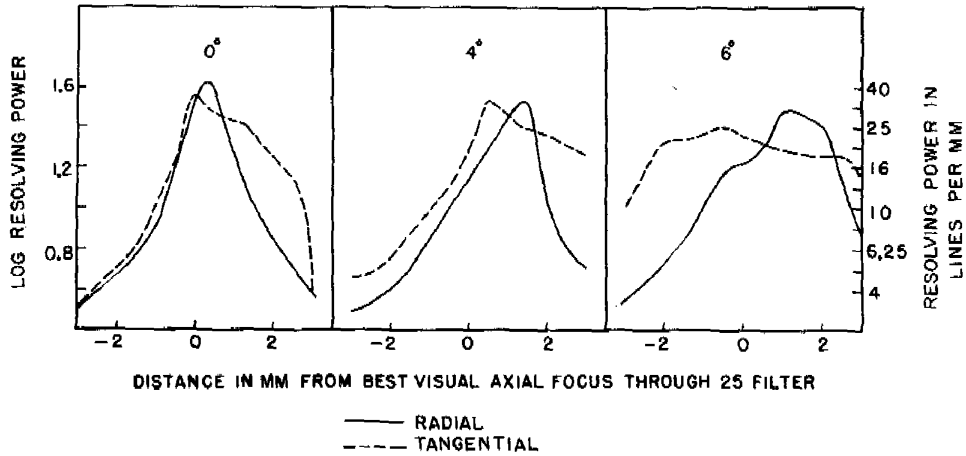

FIGURE 80. Resolving power versus focal setting for 100-in. lens (Eastman Kodak Company).

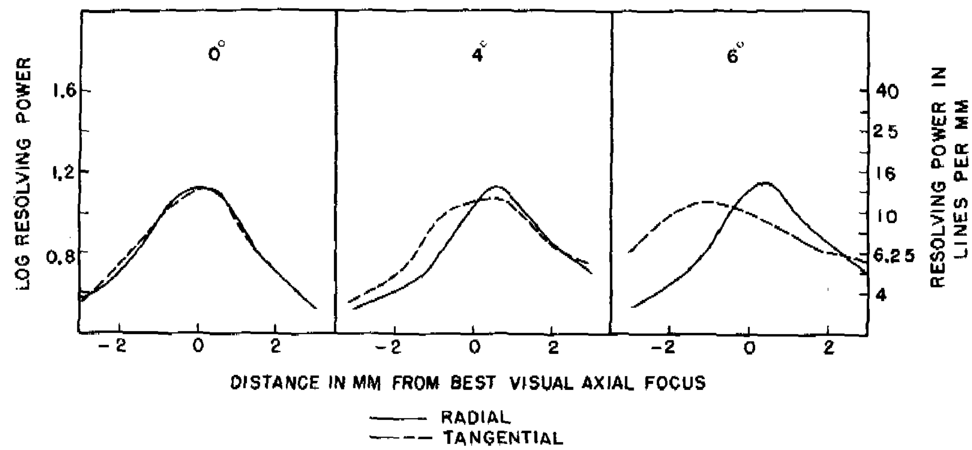

FIGURE 81. Resolving power versus focal setting for 100-in. lens at low contrast (Eastman Kodak Company).

smaller, if repeated tests are to agree within the uncertainty of the photographic process.

It would be desirable for all laboratories here and abroad to adopt the same testing targets and procedures, but during World War II no general agreement was reached. Since the real cause of the uncertainty is the impossibility of identifying any single measure that will represent within 20 per cent of the theoretical overall limits.

CONTRAST FACTORS

The arguments presented in the introduction (see Section 1.1) show that contrast has a very decided effect on resolution. A good lens with respect to contrast may seem to represent only

a slight improvement over a poor lens yielding almost the same resolution. On the basis of resolution alone, therefore, one cannot predict that the aerial picture from one lens is likely to be better than that from another. It is too early to comment with certainty on the importance of good microscopic contrast for aerial reconnaissance, but the following is suggested as a basis for further work.

Test data should be obtained on microscopic contrast as a function of resolution and initial target contrast. The microscopic contrast should be determined by means of precise microphotometry. As described in Section 1.1, the exposure level should be determined by means of the density of the macroscopic photometric areas whose surface brightness should equal that of the bright lines.

There are always many desirable ways of presenting test data. In every case some direct comparison should be made with similar data for perfect lens-film combinations. It is believed that a very useful method would be to determine the profile of successive resolution patterns by means of precise microphotometry, standardized by characteristic curve and constant density of the large photometric area. After reduction to an intensity scale, a plot would be made of the equivalent microphotometer curve, where the ordinate is in true intensity units in percentages of the intensity of the photometric area, and where the abscissa is a true linear scale of lines per millimeter greatly enlarged, with the coarse to very fine patterns all on the same basis.

Such a well-determined curve could be compared by superposition, or on the same plot, with the perfect lens-film result. The observer could then tell at once the loss of intensity in the bright lines, the gain of intensity in the dark lines, the contrast, and the rate of change of these quantities with lines per millimeter down to the limit of resolution. It is evident that the microphotometer would have to have excellent resolution in order to reproduce reliable measures on the finest patterns now resolved at peak performance by many modern lens types.

A complete lens test would then include a number of such curves according to focal setting, field angle, tangential or radial resolution, color, etc. Corresponding tests in the air would indicate haze effects, motion, etc. Finally, complete wedge patterns based not only on single line images but also on resolution patterns at different contrasts should accompany the microphotometer data. Perhaps the whole story could be told by an expansion of the wedge method, quite independently of microphotometry, provided the final patterns are replotted to constant coordinates.

Exposure Level

Consideration of all the many problems involved in evaluating laboratory lens tests on an exact comparative basis leads to the conclusion that the absolute exposure level with respect to macroscopic photometric areas should be held constant. In general, the exposure should be adjusted at the level most nearly representative of optimum picture quality by area. A lens with heavy vignetting should have its exposure adjusted not for the center but for a mean zone of the field. Likewise, in testing resolution the exposure should *not* be adjusted at each field angle to favor maximum resolution, since a plot of such peak resolution versus field angle is unrepresentative of the aerial performance of the lens.

Any lowered resolution caused by inadequate exposure due to vignetting or to washed-out dense images in the center of the field, when the average exposure is correct, is a true property of the lens and should be considered in the testing. It is very likely that if close attention is paid to such details, the laboratory differences in resolution between the old style lenses and the newer types will be much more marked, and more in accord with the observed differences in quality of the aerial pictures.

1.4.6 Film Properties

Examination of the curves in Figure 2 with respect to proper exposure level for maximum resolution shows that for Super-XX at 1/0.5 contrast the density of macroscopic areas equal in brightness to the white lines should be 1.6. For Pan-X at the same contrast and maximum

[redacted]

resolution, the density should be 0.84. Under these conditions Super-XX will resolve 32 lines per mm and Pan-X 36 lines per mm. For maximum resolution at contrast 1/0.5, Super-XX is only 1.5× faster than Pan-X, partly because the optimum density for white lines is twice as great (1.6) for the former as (0.84) for the latter.

For most favorable tone reproduction, Super-XX at 1/0.5 target contrast has its optimum exposure for maximum resolution somewhat above the middle of the characteristic curve, therefore favoring areas within cloud shadows. For the same location on the characteristic curve (density 1.6) and about the same contrast, Pan-X resolution falls to 31 lines per mm, almost identical with Super-XX performance, and requires 5.4 times the exposure of Super-XX.

For best tone reproduction, Super-XX at 1/0.125 target contrast has its optimum exposure and maximum resolution still at density 1.6 and resolves 43 lines per mm. Pan-X now resolves 52 lines per mm and requires as before 5.4 times the exposure. Super-XX has a longer straight line portion of the curve, almost entirely on the low density part of the scale, and is therefore superior to Pan-X for tone reproduction at low exposure levels. Super-XX has a somewhat higher level of fog.

All of the above provisional data are based on the high gamma of 1.9 for Super-XX, as compared to 1.5 for Pan-X. For aerial purposes with improved lenses, such gamma values are too high. A laboratory development gamma of 1.3 would probably overcome the average effect of haze on macroscopic areas. Consequently, all of the above comparisons should be reviewed from data determined at a gamma of 1.3.

It appears provisionally that for the same final range of tonal values favoring low lights and moderate contrast, Super-XX and Pan-X have comparable resolution. The fine-grain character of Pan-X probably cannot outweigh the factor of 5.4 in speed of Super-XX over Pan-X especially when vibration, movement, and exposure problems are considered. The whole subject needs further investigation, inasmuch as aerial results at Bedford indicate significantly better results on Pan-X. It is clear that for daytime tests of mounts, high-contrast, medium-density exposures on Pan-X are best. For general landscape objects, particularly in the presence of haze, Super-XX is probably best. For laboratory testing both films should be used whenever feasible. If that is not possible, then the choice should fall to Super-XX.

1.5 SCHMIDT CAMERAS

The growing popularity of the Schmidt camera in science and industry during the years immediately preceding World War II led a number of workers in the field of optical instruments to propose Schmidt cameras for military uses. Only a few proposals were considered for purposes of aerial photography, owing primarily to the limited angular coverage of the Schmidt camera, the inconvenience of curved film, and the great shutter difficulties.

The Schmidt camera still represents the simplest solution to the problem of obtaining a very fast lens system covering a moderate size field with critical definition. Other systems like the Yerkes wide-angle symmetrical system excel in one or more points, but the Schmidt camera cannot be overlooked for general utility.

1.5.1 Two-Mirror Schmidt Camera (Mount Wilson)[21]

Two Schmidt cameras (12-in. $f/1$ and 24-in. $f/2$) were developed by the California Institute of Technology under direct Army contract in 1941. The Mount Wilson Observatory, under Contract OEMsr-101, initiated in 1941 a Schmidt camera project for both day and night photography. So little was known throughout most of World War II regarding the ultimate limits of resolution in the air that it was deemed worth while to construct a 2-mirror Schmidt camera with critical definition over the entire field of view, and to provide this camera with a separate shutter.

The 2-mirror Schmidt camera is similar in principle to the ordinary Schmidt camera. A secondary convex spherical mirror, concentric with the primary concave spherical mirror sur-

face, forms an image on a curved focal surface concentric with the common center of the two mirror surfaces, and located just behind the primary mirror. The negative secondary mirror converts the system as a whole into a telephoto system.

The common Schmidt camera has a length about twice as great as the focal length. The 2-mirror form is only approximately as long as the focal length. Indeed, the curvature of the focal surface about the common center of symmetry requires that the radius of curvature and the distance of the film from the correcting plate be equal to the focal length.

The magnification caused by the secondary mirror increases the f-number of the system in proportion. Also, the correcting plate in a 2-mirror Schmidt at $f/2.5$ has the curvature and form of an $f/1.25$ ordinary Schmidt as modified by partial correction from the secondary mirror. For astronomical use over a wide spectral range, the color aberration of the $f/1.25$ simple Schmidt plate would probably be noticeable; for aerial photography, however, there is still a wide margin of tolerance.

Figure 82 shows a schematic view of the complete installation in the well of a B-17 bomber ready for flight. The drawing presents graphically the optical and mechanical details of the 2-mirror Schmidt system.

The louvre shutter is carried by suspension rods on the main framework of the camera mount. The shutter therefore occupies a fixed position in the airplane. The connection between the shutter and the correcting plate is made light-tight by means of a flexible bellows.

The following is a tabulation of the optical constants of the 2-mirror system.

TABLE 8. Optical constants of the 2-mirror Schmidt camera (in.).

Effective focal length	30.0
Focal ratio	$f/2.5$
Effective focal ratio	$f/3.4$
Radius of curvature of primary mirror	27.5
Diameter of primary mirror	16.0
Radius of curvature of secondary mirror	19.0
Diameter of secondary mirror	7.5
Diameter of correcting plate	12.0
Diameter of film	5.5
Angular diameter of field	10.5 degrees

The space between the back of the primary mirror and the film is approximately 1 in. This distance is stated to be too small for a focal plane shutter, but could have been increased had general sentiment in 1942 been in favor of focal plane shutters. Any future development of apparatus of this type might very well consider the problem anew.

Photographic tests of resolving power on high-contrast targets gave the following results:

TABLE 9. Resolution measures on Super-XX film with 2-mirror Schmidt camera.

Distance off axis (degrees)	Radial (lines per mm)	Tangential (lines per mm)
2.75	27	24
2.0	30	30
1.0	30	27
0.0	30	27
—1.0	27	30
—2.0	30	27
—2.75	30	27

The mean resolution would therefore indicate an equivalent target contrast in the neighborhood of the microscopic image of 1/0.4. The departure from the ideal resolution at $f/2.5$, in the vicinity of 65 lines per mm on Super-XX at high contrast, can be ascribed to imperfections of figure of the correcting plate and to flexure of the primary mirror. Had more time been allotted to the Schmidt camera, the figuring could easily have been carried to crisp image quality. It is probable, however, that the system is already of adequate quality for experimental flights, especially at night with photoflash bombs.

For a time it was thought possible that the correcting plate might be replaced by one or more achromatic meniscus lenses, following the published work of Maksutov,[16] and that the negative paraxial power of these lenses could serve to displace the focal surface far enough back to allow for insertion of a focal plane shutter. Computations made at Harvard established, however, that for a system of this kind the demands upon spherical correction are too heavy to be met by any practical form of achromatic meniscus lens or pair of lenses. Moreover, even with meniscus lenses of reduced

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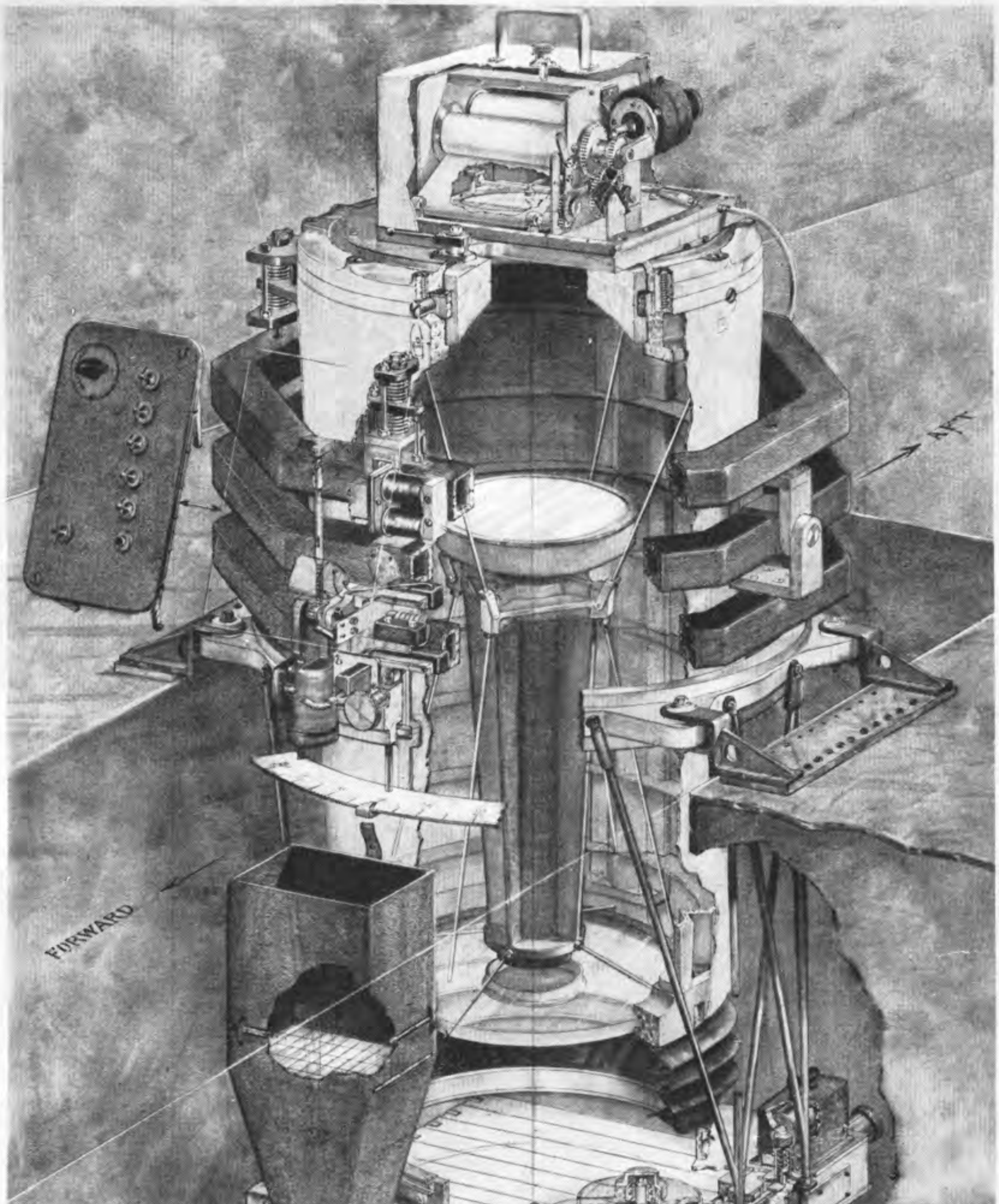

FIGURE 82. A schematic view of the 2-mirror Schmidt and installation.

[redacted]

power that still require figuring, the oblique spherical aberration introduced into the corner image is much larger than reasonable tolerances. Color correction, on the other hand, was found to be nearly as good as that of the correcting plate alone.

A description of the 2-mirror system made at Mount Wilson follows.

Camera Frame

The camera frame consists of two Meehanite castings, one holding the correcting plate and the other the primary mirror. The secondary mirror is very ingeniously held in position by twelve light rods under tension. This method makes use of the spherical symmetry of the secondary mirror. Four spider rods near the correcting plate fix the center of curvature of the mirror relative to the correcting plate. The other eight rods in tension permit a swing-like adjustment of the secondary mirror around its center of curvature. Any tendency of the secondary mirror itself to oscillate will not affect the resolution, since the primary vibration will keep the surface of the mirror in its own sphere. The longitudinal rods under tension also tend to minimize longitudinal vibration and adjustment of rod length is used to locate the secondary mirror relative to the correcting plate.

The mounting of the primary mirror was a source of difficulty. The position of the camera in the air requires that the mirror be edge-supported. In addition, the nearness of the film to the back of the primary mirror, necessitated by considerations of protecting the film from direct fogging by stray light around the secondary mirror, required the primary mirror to be thinner than otherwise desirable. Finally, the size of the photographic field requires that a large hole be cut in the primary. All of these circumstances are unfavorable for proper support of the primary mirror surface, and apparently in practice caused flexure greater than desirable. The secondary mirror caused no difficulties of this kind.

The main tube was made light-tight by cover sheets of aluminum. Gelatin filters mounted without glass in light brass frames fit a shoulder in the opening in the primary mirror.

Adjustment of the optical alignment is accomplished chiefly by lateral movement of the primary mirror. The secondary mirror is located initially by mechanical measurement, together with adjustment of the tension rods. Finally, the focal surface is adjusted by push-pull screws until it also is concentric with the mirror surfaces.

Focusing of the camera is accomplished by longitudinal movement of the secondary mirror, or by movement of the film magazine. A movement of the secondary mirror along the optical axis by the amount x produces a movement of the focal surface by an amount $3x$.

Antioscillation Mount

The camera mount is designed for maximum protection from angular vibration, and to a lesser extent from translatory vibration. The latter is accomplished by providing Lord-type shock absorbers at the four support points between main frame and airplane bracket.

The camera is mounted on three octagonal rings in a double gimbal suspension, which at the same time provides for a sweep mechanism to overcome ground motion of the plane and for elimination of vibration by means of fluid dampers and elastic restoring forces. Briefly, the lowest ring carries three ball-bearing rollers and enables the entire camera unit to be crabbed about a vertical axis and clamped in position. A Duralumin circular ring carries the full load of the assembly as well as the louvre shutter and is connected to the air frame through the Lord mounts mentioned above.

The camera rotates through small angles around an axis parallel to the line of flight with bearings in the intermediate octagonal ring. The camera and ring together rock in a pair of bearings transverse to the line of flight. These two gimbal axes pass through the center of gravity of the camera assembly.

Damping is provided by tandem liquid-filled sylphon bellows, connected by an orifice of adjustable length. Any angular change of the camera is accompanied by a flow of the damping fluid from one sylphon to the other through the orifice. The spring rate of the sylphons is used as source of a restoring force. The damping fluid recommended is isopentane. Shake-

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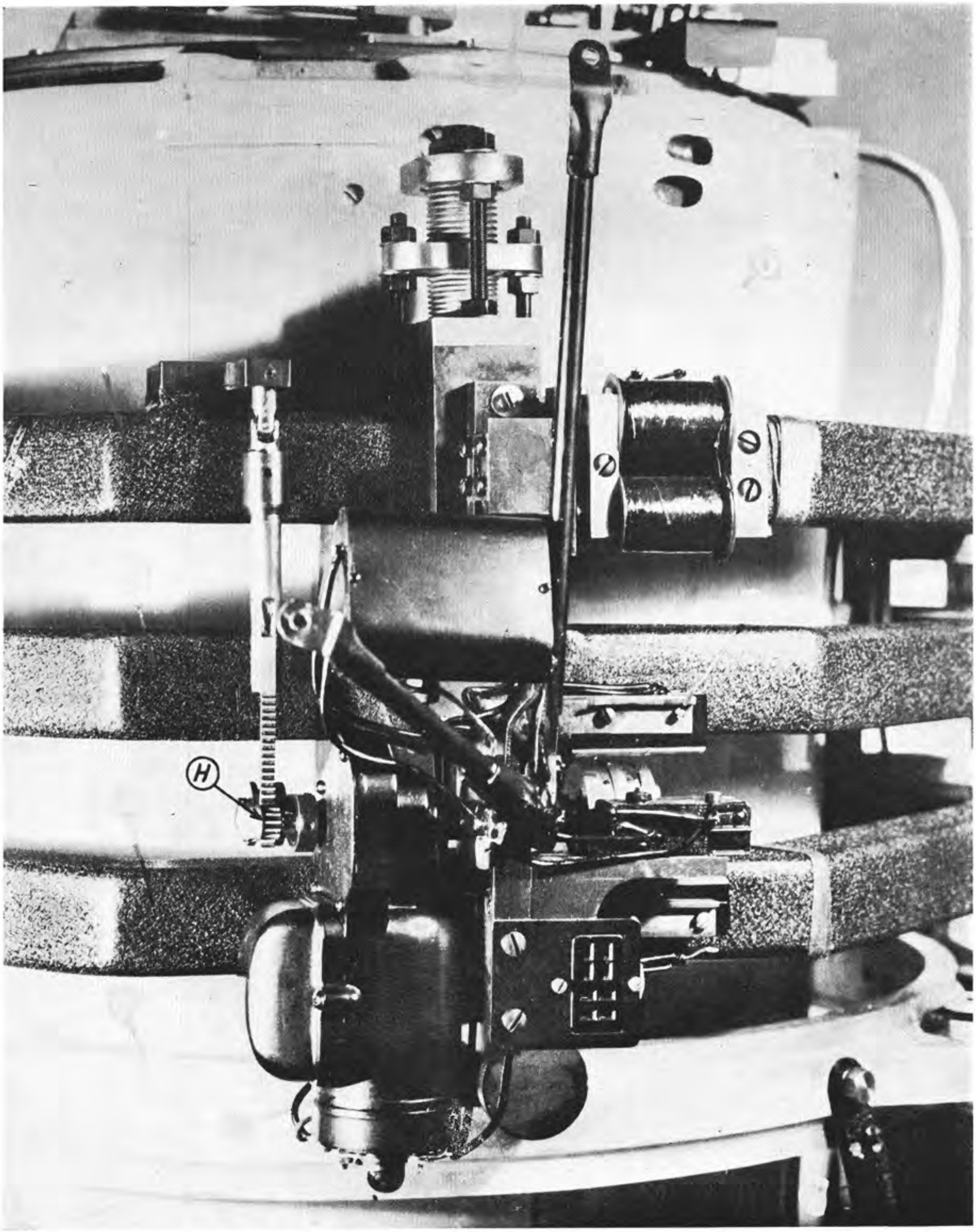

FIGURE 83. A view of the sweep and damping mechanism.

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table tests proved that transmitted frequencies were low and that high frequencies were sufficiently well filtered.

Ground Sweep Mechanism

The camera and the middle ring of the gimbal assembly must rock together about a transverse axis in order to compensate ground movement of the plane. Since the middle unit is connected for damping purposes with the upper ring, it is equally necessary that the upper ring share the rocking motion around the same transverse axis. For this reason the drive for the sweep mechanism consists of a connection of variable length between the lowest and the uppermost ring by means of rack and pinion movement. The upper ring, which is therefore directly power driven and which shares the vibrations of the plane before they are damped out, must in turn impart a rocking motion to the intermediate ring and camera to which it is only softly connected by way of the sylphon dampers.

For drive purposes, an electromagnetic clamping device is provided to tie temporarily together the upper two rings. Once the motion through the acceleration stage has passed to the camera and middle ring, this electromagnetic clamp lets go and the drive is continued only by way of the sylphon dampers, which in the meantime eliminates random vibrations during the swing. For best results the exposure has been set to occur near the end of the swing, in order that a maximum amount of time be given for damping out any vibrations imparted by the sweep-drive mechanism, or by the plane during the time the sylphon dampers are inactive.

Figure 83 shows a view of the rack and pinion drive. The electric motor, by means of a mechanical linkage provided directly by a standard type electric windshield wiper, drives the pinion H through an oscillatory motion of 140 degrees, and therefore produces a similar oscillation of the rack. The amplitude of swing is determined by the size of the pinion used. The period of the sweep is varied by means of a rheostat connected in the armature circuit of the driving motor.

Figure 84 shows the timing scheme. All operations are linked by cams and relays in such a way that the sequence of operations cannot be repeated until the next exposure is ready at the proper moment. During the cycle the film and the shutter are wound. Variation of the period does not affect the sequence or position in the sequence of the various operations.

Film Magazine

Because of the nature of the camera it was not possible to make use of standard magazines. Figure 85 shows two views of the maga-

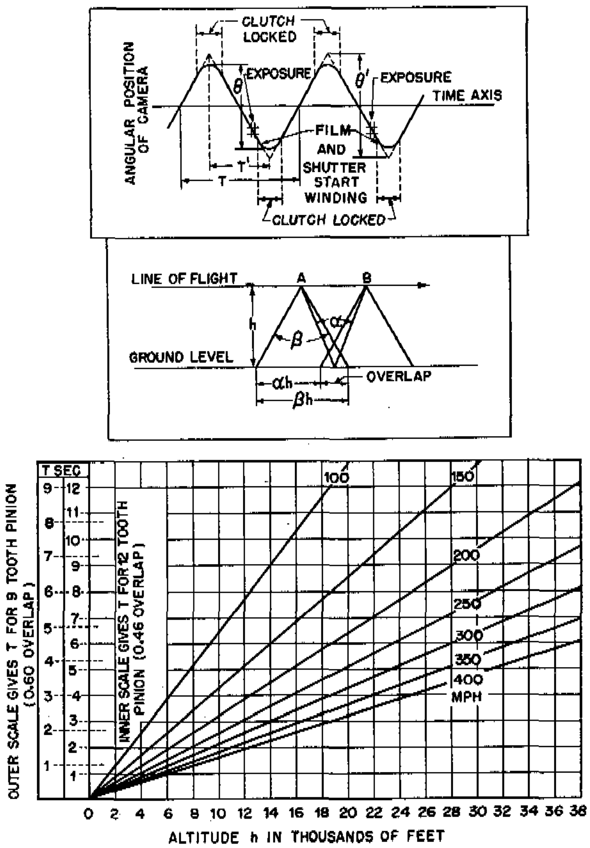

Figure 84. Timing diagrams for the 2-mirror Schmidt camera.

zine mechanism. In principle the use of the vacuum and film metering mechanisms is very similar to those of the standard magazines. There are a number of well engineered details that are attractive. One of these is the use of braking action by converting the electric drive motor into a generator on the cutoff of power by the relay by introducing a resistance of 1.5

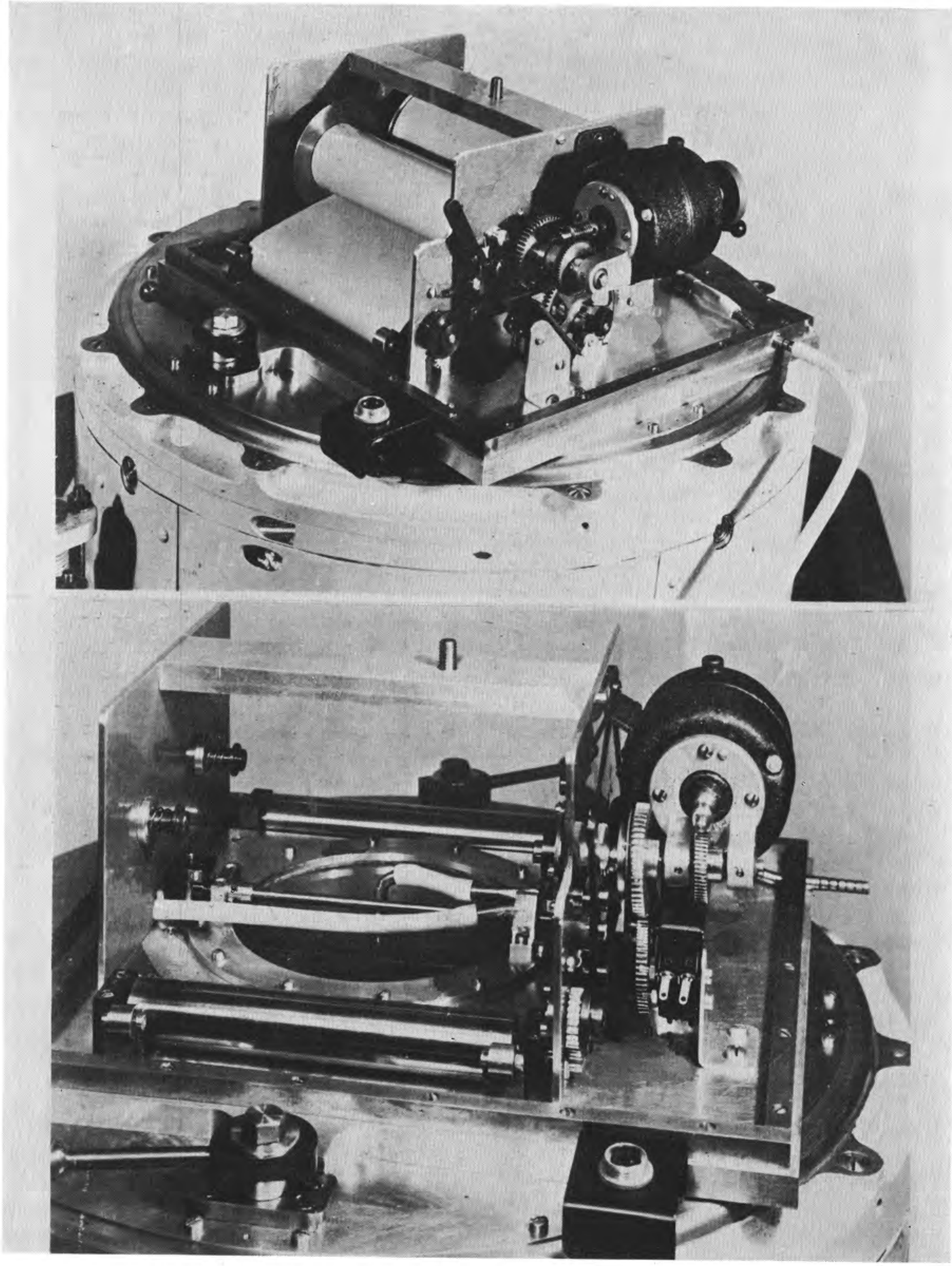

FIGURE 85. The magazine mechanism for the 2-mirror Schmidt camera.

ohms across the armature. This type of braking at the same time provides a shock absorbing action that is protective to all mechanisms. It is recommended that the minimum cycle of operations occupy about 2 sec.

The film itself is deformed to the 30-in. radius of the focal surface by means of a vacuum. The backing sphere is made of ground glass and is provided with radial slots to aid in obtaining greater uniformity of fit between film and sphere. The depth of the bending is of the order of 0.1 in. Such a deformation requires relatively slight stretching of the film. The vacuum is needed more for positioning the film than for stretching purposes. It was found that a pressure of 5 cm of mercury was sufficient for holding the film in position.

In order to hold the vacuum it was necessary to provide a light steel clamping ring that is activated by a cam on the same shaft that drives the rotatory vacuum valve.

Louvre Shutter

A considerable amount of development work had already been accomplished at the California Institute of Technology on louvre shutters in connection with the two earlier Schmidt cameras furnished under direct contract with the Army. The experiences with an air-driven louvre of high speed were used in the design and construction of the louvre shutter for the 2-mirror Schmidt camera.

The louvre shutter has a clear aperture of 13¼ in. and is carried below the correcting plate as described above. In order to provide for crab adjustment of the camera in azimuth, the bellows connection for light-tightness was fastened to a light aluminum ring that in turn rotates in a light-tight groove. Thus, the bellows can follow the rotation of the camera assembly without requiring rotation of the louvre shutter.

The shutter has ten blades which rotate through 180 degrees on ball-bearing shafts by means of pinions meshing with a rack. On each successive exposure the direction of travel of the rack is reversed.

The rack bar contains V grooves on each side and is guided by a series of ball bearings confined by additional V grooves in the stationary guide bars supporting the shutter. One end of the rack bar carries the actuating rod which is driven by a coiled spring in a spring housing. The other end of the rack bar carries the friction damping rod *R*.

The spring drive is so arranged that it drives the rack bar in either direction according to the cycle of the shutter. A spring detent pin falls behind a steel projection on the rack bar to hold the shutter blades fixed while the spring is compressed. Release of the detent, by means of a magnet connected to the switch and cam mechanism on the sweep drive, operates the shutter.

The rack bar is brought to a shock-absorbed stop by means of a dry-friction damper. This damper is mechanically very simple and effective. In principle, a loose sleeve fits over the rod that forms the end of the rack bar. Stops are arranged on the rack bar in such a way that the sleeve has a definite free range to allow for uninhibited movement of the shutter in either direction during the exposure. Near the end of the stroke, the stop engages the sleeve which in turn is made to slide with considerable and adjustable friction in an outer cylinder. Thus, the energy of the moving shutter is used up rather quickly and smoothly in forcing the sleeve through the outer cylinder. Adjustment of the friction is provided by tapered joints and screw threads.

For varying the exposure time with the spring drive, a dynamic principle was used rather than any device that might encounter the disadvantages and uncertainties of adjusting either the friction or the tension on the spring. Part of the energy of the spring is diverted into rotation of an auxiliary flywheel. The design is so arranged that the retardation varies during the exposure in a way that improves shutter efficiency. The energy stored in the rotation of the flywheel tends to release itself near the end of the stroke, where the energy from the spring drive has greatly diminished.

The shutter blades are made of aluminum. The design is carefully engineered to prevent light-fogging. Each of the shutter blade shafts which carry the driving gears has two ball bearings, while the more or less unloaded shafts

[redacted]

at the opposite end of each blade have a single ball bearing.

Tests were made of shutter speed and efficiency by means of photographs of oscilloscope traces. The fastest setting gives an effective exposure of 14.5 msec, or about $\frac{1}{70}$ sec. The efficiency characteristic of louvre-type shutters is very low, in this case only 54.7 per cent. The total exposure time is accordingly almost twice the effective time and amounts to about $\frac{1}{40}$ sec. Efficiency improves as the exposure time increases, owing to the flywheel action.

The low shutter speed for a 30-in. focal length puts a very heavy demand on both the antioscillation features of the camera and on the ground sweep mechanism. Assuming that the latter features are nearly ideal, however, it is evident that at the effective speed of $f/3.4$, very fine grain film can be used. Aerial tests of the equipment would be highly desirable.

In addition to low efficiency, the louvre shutter tends to cause loss of contrast in the aerial image. In the position of the blades on either side of the center of the exposure, where the apparent cross section of blades and openings are equal, diffraction smears out the resolution altogether. In the opening and closing phases of the shutter, therefore, in one direction on the film, the light must be considered as fogging light, rather than as useful light.

In further work carried out on Schmidt cameras for daytime photography, based on any special advantages that may be found over lens types, it would be advisable to adapt a focal-plane type shutter to the camera. It seems more likely that the Schmidt camera will find an application for night photography in view of its fast speed and maximum photographic contrast. The present instrument probably represents the nearest approach that can be made to an effective utilization of the Schmidt camera for daytime photography over an appreciable film area.

1.5.2 Two-Mirror Solid Schmidt Camera (Mount Wilson)[22, 23]

The constant need throughout the war for lenses of short focal length and high aperture, which was further increased by the introduction of the flash discharge method, led to the initiation of several projects making use of Schmidt cameras. One of these is known as the solid glass Schmidt camera in its 2-mirror form, developed at the Mount Wilson Observatory.

Figure 86 shows the optical system and mounting, inserted in a standard 24-in. between-the-lens shutter. The clear aperture is 3 in., and the focal length is also 3 in., so that the

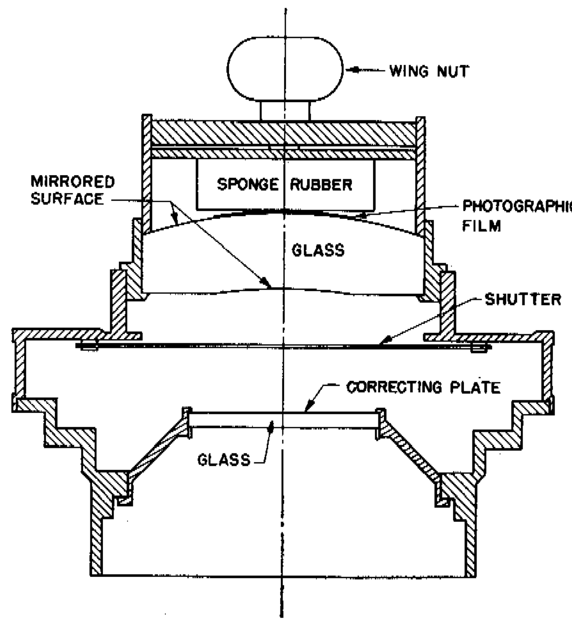

FIGURE 86. $f/1.4$ 2-mirror solid Schmidt in K-17 shutter.

relative aperture is $f/1$. The loss of light caused by the secondary mirror is so large, however, that the effective speed is $f/1.4$.

The optical design of the solid glass Schmidt is similar to that of the 2-mirror Schmidt camera discussed in Section 1.5.1, except that a glass medium has been substituted for air. One gains in speed by a factor of n in the f-number, so that an $f/1.6$ air Schmidt would perform at $f/1$ in glass. Moreover, the optical aberrations of the glass Schmidt at $f/1$ are identical in character and magnitude with those of the air Schmidt at $f/1.6$.

The most serious aberration of the solid glass Schmidt camera, unfortunately, is lateral color,

[redacted]

which ordinarily is the most serious aberration that affects resolution. Thus, good performance cannot be expected of the solid glass Schmidt in even fairly restricted fields at the focal length used. Limitation of the spectral range by means of filters is not adequate for overcoming the large amount of lateral color present.

Figure 87 shows a star field photographed with the solid Schmidt camera. The radial elongation of images in the outer part of the field is evident to the eye. It is clear that the optical system must be achromatized before any useful results can be realized with this form of camera. On the other hand, if this achromatization can be realized, there are very few other difficulties remaining. The system is compact and adaptable to standard equipment. The film can easily be deformed to fit the 30-degree field by pressure from a flexible pad.

It is probable that the system is not as useful as the Rochester $f/1$ lens with curved field, and that further efforts might appropriately be confined to such lenses. If the solid glass Schmidt were achromatized to give the same performance as the $f/1$ lens, it is probable that the same number of elements would suffice for an improved all lens system of greater field, and that aspheric surfaces could be avoided.

1.5.3 Schmidt Camera for Use With Electric Flash Night Photography (Harvard)[24]

Early in 1945 an adaptation of the ordinary Schmidt camera for night photography was

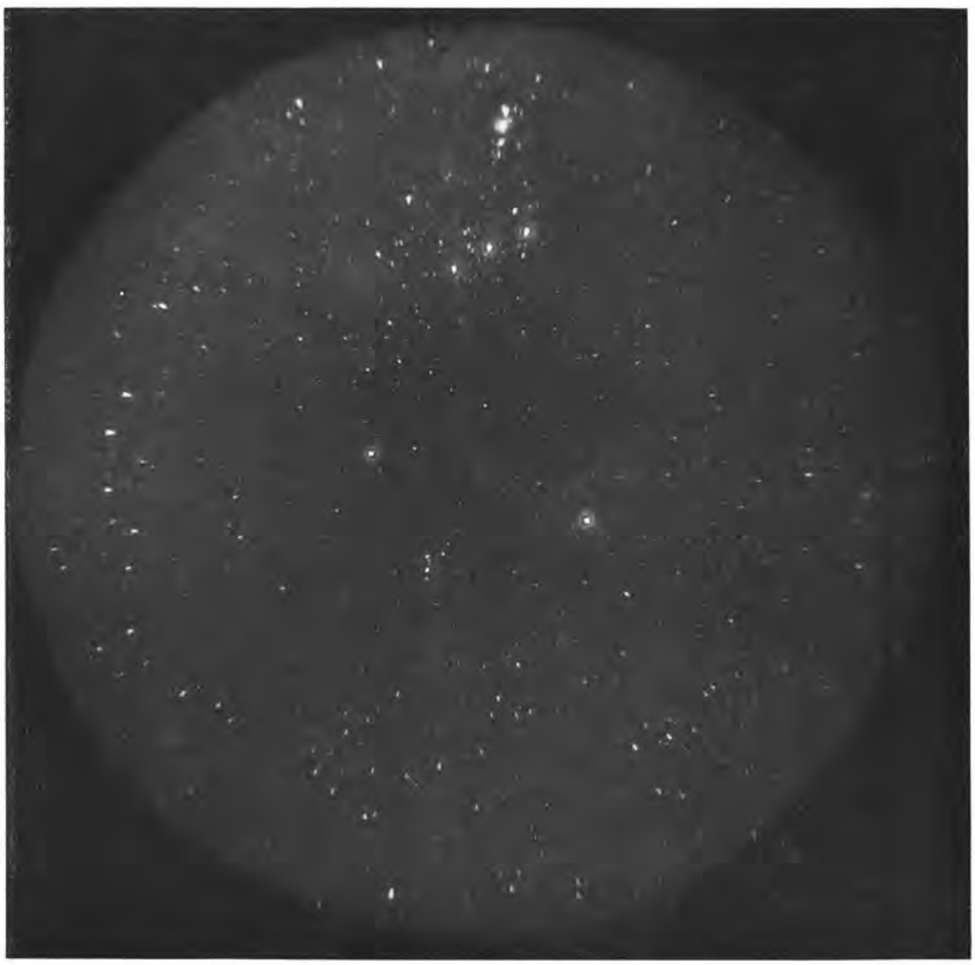

FIGURE 87. Star test with $f/1.4$ Schmidt.

[redacted]

proposed under the Harvard contract, of particular use with the electric flash system. During March and April of 1945 a prototype was built in the form of an inexpensive mockup for test purposes.

The fundamental development leading to the type of Schmidt scheme proposed is that roll film can be made to fit a spherical focal surface, provided the film is narrow relative to the length of the picture along the roll. The experience at hand with vacuum and pressure methods proved that good contact on a spherical surface can be obtained over very large areas of field. The roll film Schmidt camera can also make use of such pressure or suction, if necessary, but to a large extent gains its field of view by a very long picture across the line of flight, and a relatively short picture with overlap in the line of flight.

The prototype model made use of unperforated 35-mm film, pressed to a sphere of 5-in. radius with a picture size of 1x4 in. The predominant curvature along the 4-in. direction is followed by the natural rolling of the film around the curve. To aid in holding the film against the focal surface, the film is kept under moderate tension and the outer edges of the film are pressed against the defining sphere by means of spring riders on either side. Contact within 0.002 in. over the entire picture area was observed.

Figure 88 shows the prototype design. The heavy black line represents the path followed by the film, which is allowed to move continu-

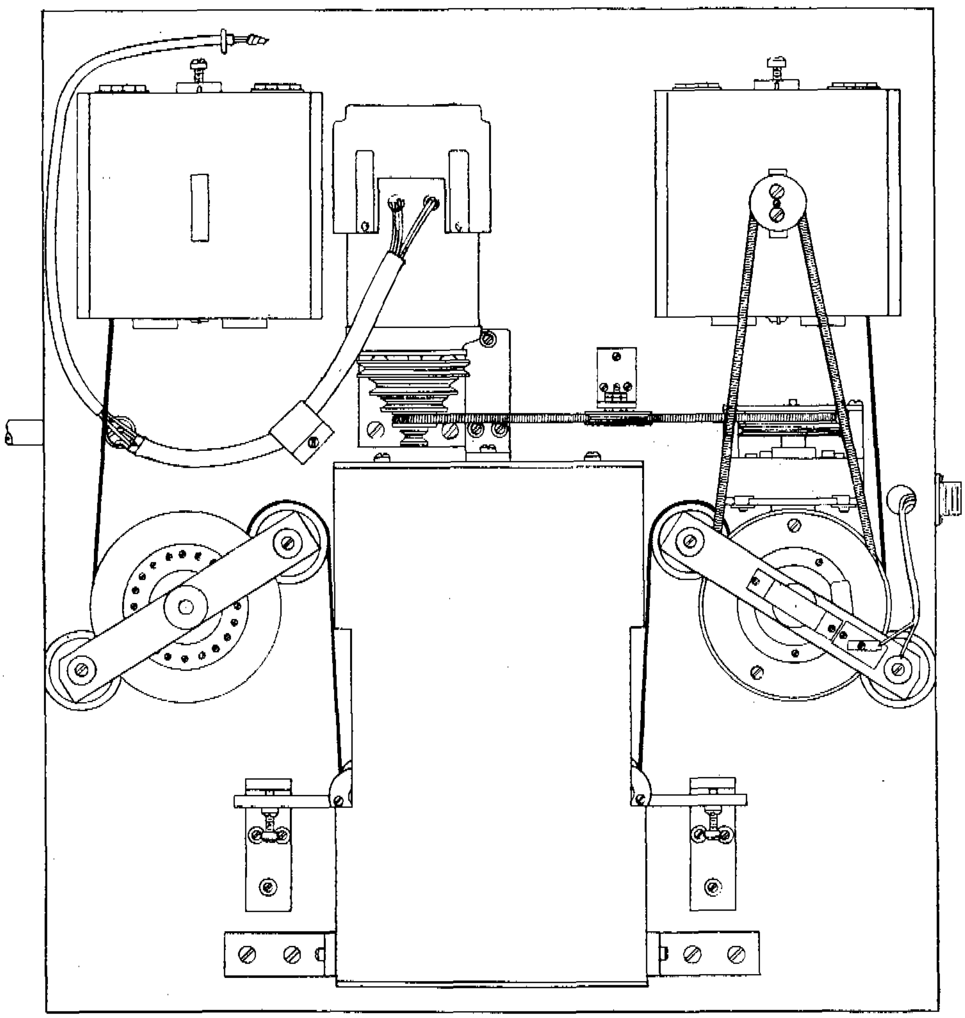

FIGURE 88. Prototype night flash Schmidt camera.

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ously, even during the exposure, because of the short focal length and short exposure time of the flash unit. Tension on the moving film is provided by a braking action on the left-hand spool. The film, on its way into the Schmidt camera, passes under rollers just below the level of the spherical focal surface. With tension and edge pressure, the film moves along at a constant rate, always maintaining contact.

The angular dimensions of the picture in the prototype model are 11x45 degrees. Synchronization of the flash exposure time with length of film produces the desired overlap in the 11-degree direction. The 35-mm film then shows a series of pictures, each 4 in. long, representing a 45-degree transverse coverage, and each with some overlap relative to the preceding picture. The film is intended for contact printing directly, whereafter the roll of prints is cut up and spliced together to give a final print 4 in. wide and as long as the run taken. It is estimated that 200 ft of film will provide a mosaic covering 120 miles long by 45 degrees wide.

A second much smaller model was constructed for production purposes. This model is shown in Figure 89. The principles are much

FIGURE 89. The 16-mm night flash Schmidt.

the same, except that 16-mm unperforated film is to be used. The aperture is $f/1$ with plastic optics. The device was intended for a small recording camera for night bombing purposes with planes making use of very small flash equipment. The end of World War II prevented testing of the one unit that was nearly completed.

A third production unit was planned and partially constructed. This system was to contain a quartz mirror and was to be mounted for constant focus by means of Invar connecting rods between mirror and film. The rest of the camera was to be designed primarily for compactness. Two 10-in. diameter quartz mirrors and one correcting plate were completed before the end of the Harvard contract. These systems were to operate at $f/1$ with 8-in. focal length.

1.5.4 Miscellaneous Proposals and Data

An $f/1$ Schmidt Camera with 8-in. Focal Length

Experiments made at the Chicago Aerial Survey Company indicated that photographic roll film could be forced temporarily into extreme spherical form by use of hydraulic pressure. To this end work was begun on an ordinary Schmidt camera under Harvard Contract OEMsr-474. A 10-in. diameter Pyrex mirror was to be used in connection with this camera. The system was later discontinued because of interruption of the experimental work on the film mechanisms, and the correcting plate was thereafter used in conjunction with the 10-in. quartz mirror for the Schmidt described under Section 1.5.3.

An $f/1$ Schmidt Camera with 8-in. Focal Length for Use in Strip Photography[24b]

Work at the University of Rochester on searchlight strip photography indicated that a strip Schmidt camera would be of considerable promise. Briefly, the ordinary Schmidt was to be folded by means of a 45-degree mirror between correcting plate and spherical mirror. Parallel light on axis was to pass through the correcting plate, be reflected from the 45-degree mirror to the primary spherical mirror, and then converge to a focus through a narrow slit opening in the 45-degree mirror. Roll film stretched on a surface of double curvature was to move past a curved slit across the focal surface. The speed of movement of the film was to be synchronized with the speed of the airplane in the usual strip fashion. Finally, the

camera was to be boresighted with an illuminating searchlight so arranged that ground illumination covered only slightly more than the projected image of the slit in the focal surface of the Schmidt camera.

The end of World War II interrupted this work, which for a long time was given low priority. A 12-in. Pyrex spherical mirror was finished, and a blank for a correcting plate was brought to plane parallelism.

Approximate Ray-Tracing through an $f/1$ Schmidt Camera[24c]

Table 10 represents a compilation of image errors found in an ordinary $f/1$ Schmidt camera of 8 in. focal length, as provided by Harvard from approximate formulas. The figures should agree with exact calculations within 10 per cent. Figure 90 defines the rays as numbered and plots the results. The coordinates Δy and Δz are in image space on the surface of the focal sphere, and therefore represent the final intercepts of individual rays in the focal surface.

Table 10. Ray intercepts (image errors) of a Schmidt camera.

		$f/1.0$		$f/1.4$	
		Δy (mm)	Δz (mm)	Δy (mm)	Δz (mm)
14 degrees off axis	1	−0.261	0.000	−0.023	0.000
	2	−0.214	0.071	−0.012	0.018
	3	−0.115	0.080	0.008	0.016
	4	−0.036	0.041	0.014	−0.001
	5	0.000	0.016	0.000	−0.011
	6	0.035	0.041	−0.014	−0.001
	7	0.115	0.081	−0.008	0.016
	8	0.214	0.070	0.012	0.018
	9	0.261	0.000	0.023	0.000
20 degrees off axis	1	−0.513	0.000	−0.046	0.000
	2	−0.422	0.138	−0.024	0.036
	3	−0.226	0.159	0.016	0.032
	4	−0.071	0.081	0.027	−0.002
	5	0.000	0.032	0.000	−0.022
	6	0.071	0.081	−0.027	−0.002
	7	0.226	0.159	−0.016	0.032
	8	0.422	0.138	0.024	0.036
	9	0.513	0.000	0.046	0.000

The aberration is a mixture of slight astigmatism with large oblique spherical aberration. At 20 degrees off axis, the light in the zone between $f/1.4$ and $f/1.0$, which contains half the light, has considerable aberration. Vignetting can be used to a moderate degree to limit the aberration, but it is clear that contrast far off axis will be low, particularly if the central core of the image must be removed by the film holder. The better correction of the skew rays helps out to some extent.

Coordinates of an 8-in. Aperture Schmidt Correcting Plate for an $f/1$ Camera

Table 11 provides the coordinates of the aspheric curve on the face of an $f/1$ Schmidt camera of 8-in. focal length. Minimum chromatic aberration requires that the zone of zero deviation lie approximately 87 per cent of the way toward the edge. The focal length is 8.000 in., the clear aperture 8.000 in., and the radius of the primary mirror is 15.59 in.

Table 11. Coordinates of an 8-in. aperture $f/1$ Schmidt plate.

Zone height on correcting plate (in.)	x-coordinate (in.) (by series)	x-coordinates (in.) (exact)
0.00	0.000 000	0.000 000
0.20	0.000 125	
0.40	0.000 500	0.000 502
0.60	0.001 122	
0.80	0.001 964	0.001 964
1.00	0.003 040	
1.20	0.004 303	0.004 288
1.40	0.005 737	
1.60	0.007 296	0.007 290
1.80	0.008 980	
2.00	0.010 726	0.010 710
2.20	0.012 488	
2.40	0.014 234	0.014 200
2.60	0.015 855	
2.80	0.017 352	0.017 314
3.00	0.018 599	
3.20	0.019 565	0.019 488
3.40	0.020 080	
3.60	0.020 111	0.020 026
3.80	0.019 488	
4.00	0.018 162	0.018 060
4.20	0.015 855	
4.40	0.012 628	0.012 521
4.60	0.008 122	

1.6 ANTIVIBRATION MOUNTS FOR AERIAL CAMERAS[25]

After a thorough study of the theory of antivibration mounting and of types of damping, two designs were worked out and constructed for standard aerial cameras by the Eastman

Kodak Company under Contract OEMsr-392. A third design was constructed for use with the multiple camera installation in the F-5E aircraft. Symmetrically placed coil springs in compression, combined with dry friction dampers, accomplish efficient antivibration control for all degrees of freedom without compensation for center-of-gravity shifts.

Thorough testing both on the laboratory shake table and on flight tests has proved their superiority over standard mounts. It is recommended that they be used with high-resolution aerial photographic equipment.

The material in this report falls naturally in the following group arrangement: (1) Theory of antivibration mounting. (2) Descriptions of the test models and final designs. (3) Multiple camera mount for F-5 aircraft. (4) Laboratory tests of a number of aircraft mounts. (5) Results of flight tests over resolving power targets. (6) Conclusions.

1.6.1 Theory of Antivibration Mounting

The term *vibration* is understood to apply to the higher frequency range of cyclic motions, both rotational and linear in nature. More specifically, the range of frequencies from 800 cycles per minute upward has received special attention in this report. The motions arising from aircraft engine and propeller dynamic unbalance and propeller aerodynamic unbalance are therefore the subject of consideration, as distinct from lower frequencies of motion in the category of roll, pitch, and yaw.

It is recognized that only the rotational movements, and most particularly those about the longitudinal and transverse axes, are of importance as bearing upon picture definition. Antivibration mounting or filtering action against linear movements may be desirable, not only for protection of the camera from mechanical shock, but also for reasons to be pointed out shortly.

Center-of-Gravity Principle

A center-of-gravity mount is one for which the resultant force of the mounting elements is always directed through the center of gravity. Linear components of motion cannot be converted into definition-destroying rotational motion in a center-of-gravity mount because no

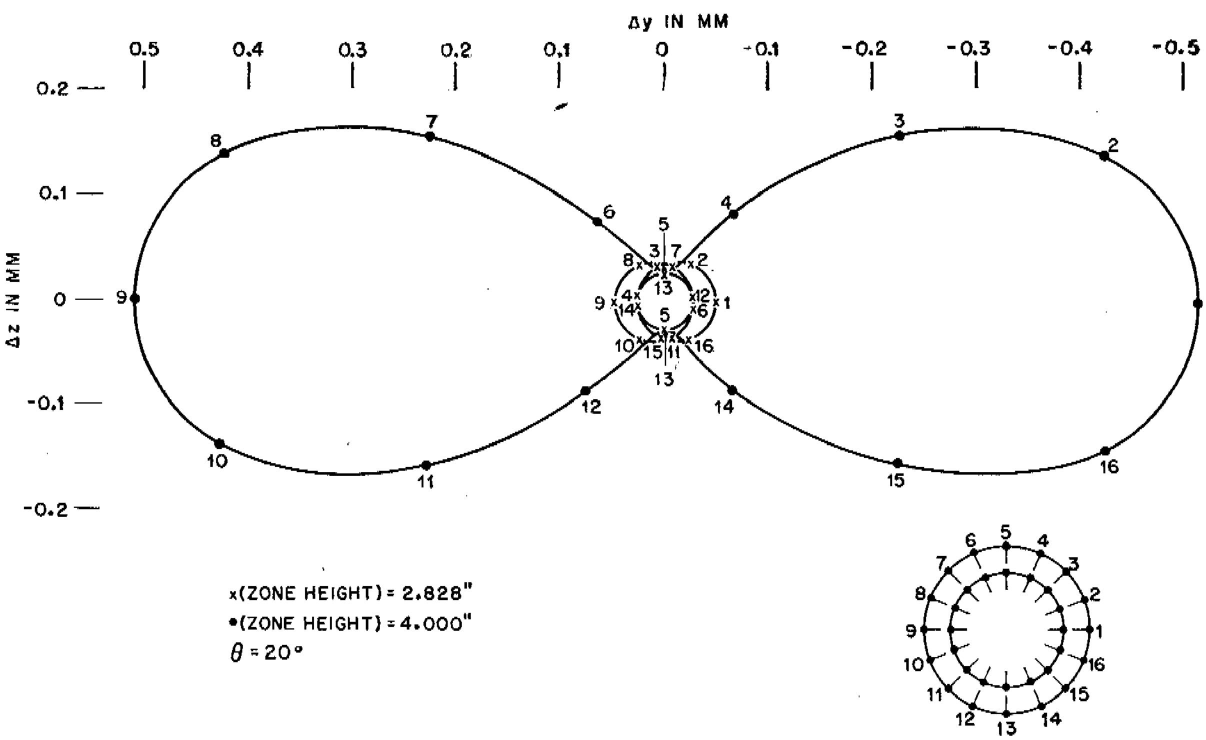


FIGURE 90. Image errors of an $f/1$ Schmidt camera.

[redacted]

torque can develop. This is true even if no filtering of linear motions is provided.

The first requisite of a good mount is, therefore, that it make use of the center-of-gravity support as far as practical. However, the center of gravity of a camera changes vertically with the amount of film load and horizontally as the film is fed from supply to take-up reel. In addition, the center of gravity with respect to the mounting trunnion varies with camera model and even between individual cameras of the same model.

Filter Action for Linear Motions

After bringing the average position of the center of gravity to the most favorable location, we still have a significant departure from the ideal in most practical cases. There remains one alternative, namely, the use of adequate filtering action for linear motions as well as for rotational motions.

To say that the amplitude of a disturbance has been reduced through the filtering action of a mount is equivalent to saying that the forces of acceleration acting on the isolated member have also been reduced to the same extent. Therefore, if we do not have a center-of-gravity mount, we can still obtain satisfactory operation if the linear acceleration forces acting at a small distance from the center of gravity are sufficiently reduced to keep the resulting angular motion within tolerable limits.

Natural Frequency

The filtering effectiveness of a mount is related to its natural frequency. The lower the natural frequency, other things being equivalent, the better the filtering action for a given disturbance. The natural frequency must be lower than the disturbing frequency in order to produce any filtering action.

Two of the elements which are always present in a mechanical filtering system are: (1) the *mass* from which the vibrations are to be filtered, and (2) an elastic support, such as rubber or spring members, which may be called the *compliant* member. If such a system, containing only these two elements, is set in motion and not disturbed by external forces of friction, etc., it will continue to oscillate at a characteristic frequency called the natural frequency. Let C be compliance measured in inches of deflection per pound of load (reciprocal of spring constant) and let W be weight of mass in pounds; then

$$F_n = \frac{187.6}{\sqrt{WC}}, \tag{1}$$

where F_n is natural frequency in cycles per minute. This formula applies to any linear direction of motion if the compliance C applies to that direction. It is of interest to note that, as applied to the vertical direction, if the spring deflects statically by the amount D inches from zero load to a load equal to W, then

$$F_n = \frac{187.6}{\sqrt{D}}. \tag{2}$$

We now consider the case of a rotational degree of freedom with a restoring torque about the axis of rotation. If k is the radius of gyration of the mass about its axis of rotation and r is the radius at which the springs act, then

$$F_n = \frac{r}{k}\,\frac{187.6}{\sqrt{WC}}, \tag{3}$$

where F_n is the rotational natural frequency in cycles per minute, W is again the weight of the mass in pounds, and C is the combined linear compliance of the springs (inches per pound).

The second requisite of a practical mount is that the natural frequency for all components, linear as well as rotational, be low. Only then is good filtering obtained for those disturbances above the natural frequency.

Low natural frequency requires high compliance or "softness" in the mount. As a consequence, a point is reached where the increased instability of the mount permits an intolerable amount of camera tilt owing to horizontal shift of center of gravity with film movement. There are other factors which place a low practical limit to the natural frequency. Examples are the stiffness of such cable connections as may be required, forces of air turbulence against lens cone, and convenience in handling. The shift of center of gravity seems to be the most important factor, however, and a figure of 80 to 200 cycles per minute is a practical range.

Damping

With a proper mounting system of low nat-

ural frequency, vibration disturbances are well filtered out, even if no damping is applied. It is for proper behavior of the mount at and near the natural frequency that damping must be supplied. The slow, continuous roll and pitch of the airplane may contain harmonics which would cause the camera to oscillate at the natural frequency with large amplitude if damping is not provided.

All disturbances of a transient nature, such as bumps and jerks from air pockets, are sure to set up oscillations, and the properly damped mount will recover from such transients in the minimum of time.

The type of damping and method of application are very important. In general, it may be said that the better the control of amplitude at the natural frequency, through application of damping, the poorer the filtering action at higher frequencies. This is true because the damping mechanism increases the coupling between camera and vibrating support, thus introducing more vibration into the camera. The effect is different for different types of damping.

Types of Damping and Method of Application

Under this heading will be treated the viscous and dry-friction types of damping as applied either directly or through the medium of an auxiliary compliance. The performance of a mount can be shown to good advantage by plotting what is called *magnification factor* (also called transmissibility) as a function of the frequency of a simple harmonic disturbing vibration. The magnification factor is the ratio of camera amplitude to the amplitude of disturbance. Magnification factor curves may be obtained experimentally on a test stand but much can be learned preliminary to the design of a mount by calculating magnification factor curves from damped vibration formulas. This method is used to demonstrate the effect of damper type and of the use of an auxiliary compliance.

Only one component of movement will be considered, and the constants will be selected to give a free (damper removed) natural frequency of 100 cycles per minute and a maximum magnification factor of 2. The curves apply equally well for either a translational or a rotational vibration, although the schematic sketches indicate only translational movement.[25a]

Figure 91 is the schematic arrangement for direct viscous damping. Viscous damping is characterized by the fact that the resisting force is proportional to the velocity of relative movement. It is obtained by the use of an oil film or by such arrangements as dashpots and bellows. Sponge rubber may be considered as supplying viscous damping, although usual de-

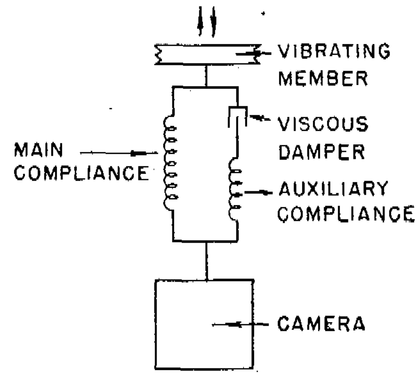


FIGURE 91. Direct viscous damping.

signs seldom supply enough damping. Figure 92 shows the magnification factor curve for direct viscous damping in a sufficient amount to bring the maximum factor to 2.

Figure 93 shows the arrangement when viscous damping is employed with an auxiliary compliance, and the magnification factor is also shown in Figure 92. The curve of Figure 92 was calculated for the case of an auxiliary compliance equal to one-half of the main compliance and the proper damping to bring the maximum factor to 2.

Even though the magnification factor does not go above 2 for the case of the auxiliary compliance, it appears from Figure 92 that resonance control is less satisfactory than that for direct damping, as the peak is broader and extends to higher frequencies. There are, however, two very important advantages which more than offset this disadvantage. The first is that the magnification factor above about 500 cycles per minute is lower and becomes inversely proportional to the square of the frequency. The magnification factor is inversely

proportional to the first power of frequency for the case of direct viscous damping. The second advantage is that the amount of damping may change over a wide range (as may happen with temperature changes, dust-clogged orifice holes, or improper adjustment, etc.) without adversely affecting the amount of filtering obtained at the higher frequencies.

In considering damping means for the first ing action. This may be best explained by remembering that the rate of energy absorption by a damper is equal to the product of force and velocity. Now, since the force for a viscous damper is proportional to the velocity, it follows that the rate of energy absorption is proportional to the square of the velocity. For the dry-friction type of damping, however, the force is substantially independent of velocity.

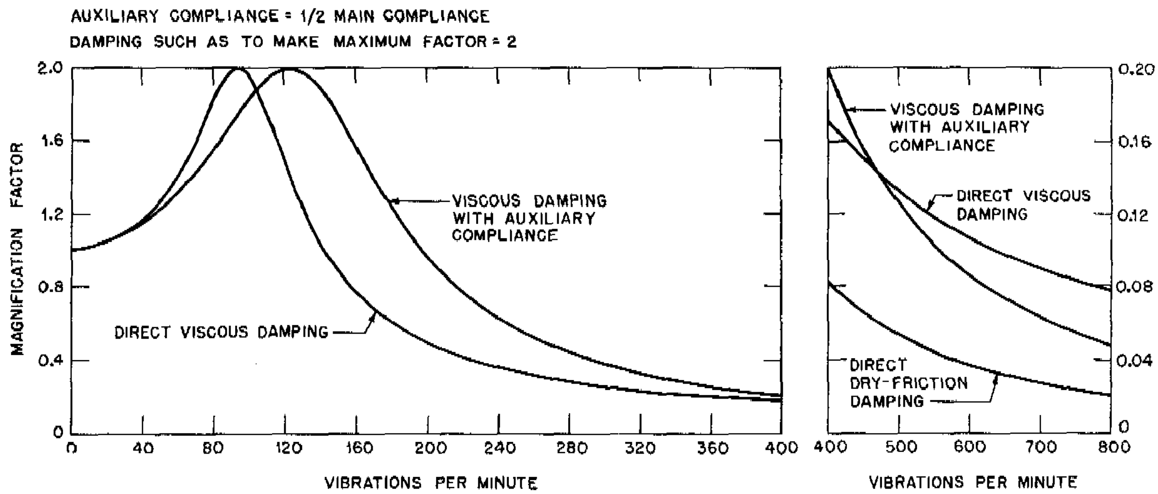


FIGURE 92. Calculated magnification for three types of damping.

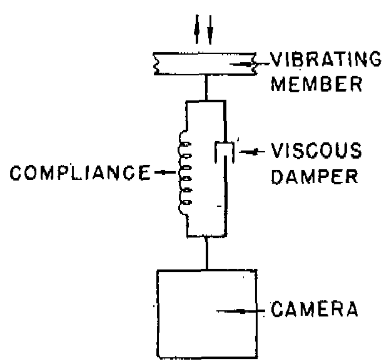


FIGURE 93. Viscous damping with auxiliary compliance.

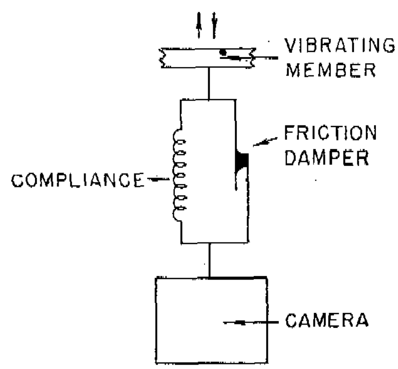


FIGURE 94. Direct dry-friction damping.

spring mount, it was decided to try dry-friction or coulomb damping because of its greater convenience. This is apparent when it is considered that one small friction unit may supply damping in two or three degrees of freedom, thus replacing several larger and more delicate units.

It was discovered that dry-friction damping also possesses an important advantage over viscous damping from the viewpoint of the filter- We may say then that the rate of energy absorption is about directly proportional to the velocity for dry-friction damping.

If we consider two different oscillating movements, both of the same amplitude but of different frequency, and if we have viscous and dry-friction dampers which absorb the same energy at the lower frequency, we shall discover that the viscous damper absorbs much

more energy at the higher frequency because, while the amplitudes are the same, the effective velocity is greater at the higher frequency. This is equivalent to saying that the dry-friction damper offers less disturbing force at the higher operating frequency, while providing adequate control at the natural frequency.

The exact nature of the dry-friction damper must be known in order to calculate correctly the magnification factor curve near resonance. The behavior at the higher frequencies is less dependent on the nature of the friction and can be calculated with adequate accuracy. Figure 92 shows the calculated curve for direct dry-friction damping for higher frequencies. The magnification factor for higher frequencies becomes inversely proportional to the square of the frequency and is lower than that for viscous damping, even with auxiliary compliance. Figure 94 gives the schematic arrangement for direct dry-friction damping. The effect of using an auxiliary compliance with dry-friction damping is almost negligible as far as filtering is concerned.

The relative performance of actual mounts may easily be calculated for one component of vibration if the natural frequency and type and amount of damping are known. If the displacement of the image relative to the film is known as a function of time, then the relative distance through which the image moves during exposure is found by observing the movement during the change of time from t_0 to t_0 + exposure time. The worst condition occurs when exposure starts just before and ends just after the time of maximum relative velocity. Therefore, if the disturbing amplitude and frequency, the magnification factor, and the exposure time are known, the blurring or movement of image relative to film during exposure can be determined. If we take the somewhat severe case of the mount support members, which are 20⅝ in. apart, having a vertical vibration amplitude of 0.015 in. 180 degrees out of phase, a rotational disturbance is set up in the camera which would produce an image movement relative to film, with an amplitude of 0.0349 in. for a 24-in. lens if the camera is mounted rigidly to the support. Figure 95 shows the maximum amount of blurring movement for 1/50-sec exposure for this case, with the three types of damping shown on Figure 92 for frequencies between 800 and 2,200 cycles per minute.[25b]

Caution must be exercised in interpreting Figure 95 in other than relative values; in the actual case, the combined effect of all components of all vibrations at different frequencies must be considered with the complicated interactions of the different components when the

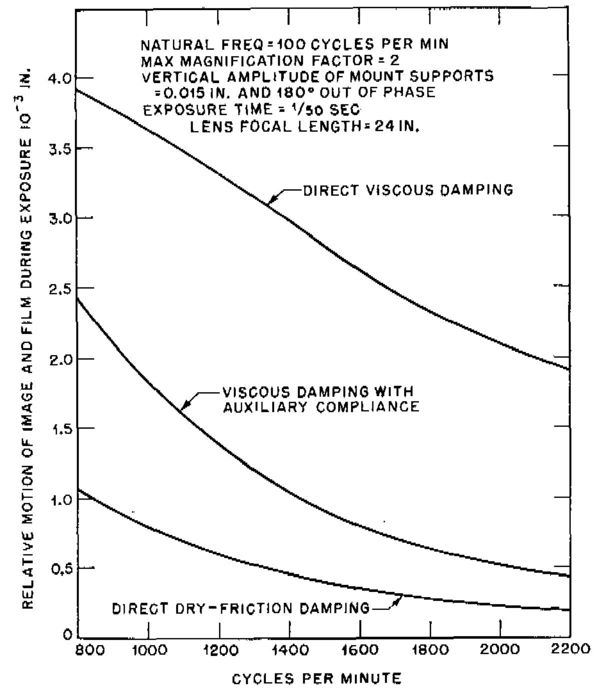


FIGURE 95. Effect of damping type upon picture blurring.

center of gravity does not coincide with the center of suspension.

The third requisite of a good mount is, therefore, suitable damping elements of which the dry-friction type has definite advantages.

1.6.2 Description of Test Models

The first experimental mount consisted of a double-ring gimbal arrangement with ball-bearing gimbal axes. An air-bellows damper was used. The bellows was of metal construction with a long leakage path through felt pads. The compliance of the metal bellows supplied the main compliance while that of the air vol-

ume acted as an auxiliary compliance for the damper.[25c] Tests proved this mount to be very effective for rotational disturbances.[25d] It was soon discovered, however, that either an accurate automatic counterbalance was needed to keep the center of gravity at the intersection of the gimbal axes or effective filtering for linear components of motion was needed.

The use of compression spring elements with friction dampers to give complete linear and rotational filtering action proved to be the simplest and most effective solution.

The first design of a spring mount made use of a standard A-8 mount. The only change was to replace the four sponge-rubber buffers with enclosed spring and friction damper units.[25e] This produced an experimental mount quickly and proved the effectiveness of the design principles in subsequent laboratory and flight tests. This model was also provided with a combination intervalometer and sweep mechanism for ground-speed compensation.

A second design was then worked out and four models constructed. Figure 96 is a photographic view of this design, and Figure 97 shows details of the spring and damper units, the trunnion clamp, and the bearing for sweep motion. These parts are shown to scale and in their correct relative heights. The outer ring of the A-8 mount is again used but the sponge-rubber pads are replaced by rigid connectors. The springs for this design are located on an internal ring structure at the corners of an imaginary rectangle 10x14 in., with the long dimension along the longitudinal direction. This

FIGURE 96. Spring mount, second design.

location of the springs gives greater stability about the transverse axis at which greater unbalance torques occur owing to film transport. The spring location in the first design was in-

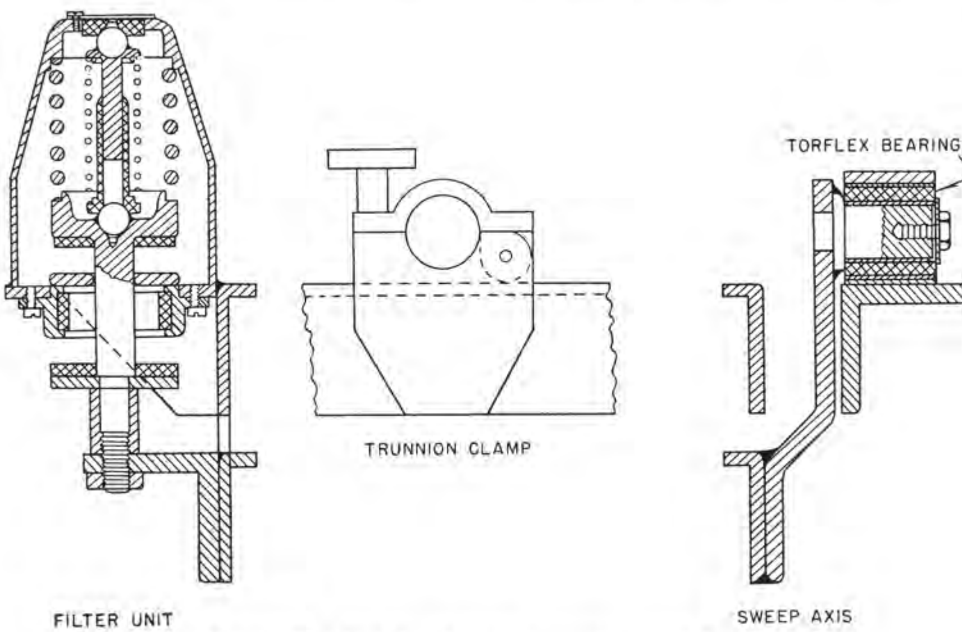


FIGURE 97. Details of spring mount, second design.

correct for this consideration. Also, the springs of the first design were in a lower horizontal plane than the average center of gravity for the K-17 and K-22 cameras with 24-in. lens. This condition is corrected in the second design. The spring and damper design of Figure 97 accomplishes symmetrical damping by means of the internal ball-and-plunger arrangement with the small loading spring. Both stainless steel balls are soldered on their lower sides to the supporting steel member, while on the upper sides they are free to slide in the synthane (bakelite fiber) sockets. By virtue of this sliding friction, damping action is provided for all horizontal linear motions. The steel plunger, sliding in the synthane sleeve, in turn provides friction damping for vertical motions. The plunger fit is not sufficiently snug for any air dashpot action. A symmetrical damper unit of compact and rugged design has thus been provided with operation in three degrees of freedom.

The camera weight and radius of gyration may be varied by about plus or minus 15 per cent without appreciably affecting the performance. The springs can, of course, be changed for other camera weights. The camera center of gravity should remain within a radius of approximately 1 in. of the geometrical center of the spring locations.

The damping friction is best determined under actual test conditions. The damper adjustment is, however, not critical. A good criterion in judging the damping action is to push the loaded mount all the way against the rubber stops (approximately 1/4 in.) in one direction, and if upon release the mount comes to rest in two or three cycles, the amount of damping is correct.

The method of ground-speed compensation, described in Section 1.6.8, calls for a variable-speed electric motor on the mount to swing the camera back and forth. The first mount arrangement places this motor on the same side of the spring suspension as the camera. It is feasible to place the motor drive outside of the spring supports as has been done in the later design. This safeguards the camera from motor vibrations without any reliance upon motor suspension.

1.6.3 Multiple Camera Mount for F-5E Aircraft

Construction of spring and damper elements for the multiple camera mount was undertaken at a somewhat later date than the development of the single camera mounts described above. A description of the multiple mount is of interest at this point because of the unique damping arrangement employed and because it illustrates the possibility of providing a center-of-gravity mount while utilizing previously designed supporting structures of apparently unsymmetrical location.

The F-5E (a photographic conversion model of the P-38 fighter aircraft) makes use of a welded frame structure of 1-in. seamless steel tubing; within this structure is another welded frame of 3/4-in. seamless steel tubing adapted to support various combinations of from one to three cameras in the nose of the ship. The vibration filtering elements are placed between the two frames to provide a support for the inner frame which, with the cameras, acts as a rigid unit.

The total maximum weight of the inner structure with cameras is approximately 220 lb.

The arrangement found to utilize best the supporting members of the frame structure already constructed makes use of two large compression springs, one on each side of the frame and 5 1/4 in. back of the combined center of gravity. Each large spring supports about 81 lb of the total load. Two smaller springs in tension are located 14 1/2 in. in front of the center of gravity, each supporting about 29 lb. The front springs are coiled loosely around a stiff steel wire calculated to give the necessary lateral compliance not provided by the tension springs. The rear springs are also below the center-of-gravity level, but the front springs are correspondingly high. The static deflection of all springs is the same (a little less than 1 in.); this is a necessary condition for a center-of-gravity mount.

Figure 98 shows the four mounting elements in correct relative position except for being crowded much closer together than they would be for normal use. The rubber-faced stops next to the large springs fit around trunnions pro-

vided on the inner structure. The caps at the upper ends of the tension springs also house stops. The picture shows quite clearly the four synthane friction pads inside each of the large springs. The lower ends of the two lower pads and the upper ends of the two upper pads are held to their respective spring end caps by a loose-fitting pin in a hole through the pad. Between each pair of pads is an expansion spring keeping the pads pressed against the inside surfaces of the large spring coils. In the normal compressed condition, the upper pair of pads telescope between the lower pair. The friction between the pads and the spring coils provides the requisite damping in all three degrees of freedom. For this type of damping, which is extremely simple and requires no extra space, it is necessary to design the spring with a sufficient number of coils to afford a good friction contact for the pads.

1.6.4 Laboratory Test of a Number of Mounts

The test stand provides a standard mount support which can be vibrated rotationally about a horizontal axis or translationally in a horizontal direction over a wide range of frequency and with adjustable amplitude. The amplitude remains constant throughout each test. The range from about 10 cycles per minute to about 800 cycles per minute can be covered with ease of adjustment to any particular frequency. The frequency is measured by the use of a strobotac and a segment disk on the eccentric shaft. Segment rings of 60, 30, and 10 divisions were found useful.

The rotational movement of the camera was measured by noting the movement of a focused light beam reflected from a small mirror on the camera. The readings were carried out in a semi-darkened room. One observer could adjust speed, read amplitude, and plot a curve directly with convenience. The resulting curve of amplitude versus frequency is in effect a magnification factor curve if the proper ordinate scale factor is applied.

The testing technique found to be most suitable requires two steps: First, a curve of response is determined for a pure rotational input (about a horizontal axis through the center of gravity of the camera for full film load) at an amplitude of 4.3 min of arc; and, second, a curve of response for pure horizontal translation (along the axis perpendicular to the axis of rotation) with an amplitude of 0.015 in. These test curves are plotted along with a third composite curve obtained by addition of the other two curves. These composite curves provide a ready comparison between mounts and of changes in a given mount.

FIGURE 98. Parts of antivibration mount for F-5E aircraft.

It is possible to report here only a small part of the tests made.[25f] The most interesting results are those for the standard A-8 mount, the A-11 mount, and the Eastman-NDRC Robinson spring mount. Figure 99 gives the test curves for these mounts. These are composite curves determined by the procedure outlined above, except for the case of the A-8 mount for which the rotation and translation components of the shake table were simultaneously applied. The composite method would show a less favorable curve for this mount.

The curves for the A-8 and A-11 mounts show two characteristic peaks. The second peak in each case is caused by the translational resonance converting into rotation. Greatly improved operation would be obtained by: (1) reducing the translational natural frequency, (2) relocating the center of gravity (the center of gravity comes much too high for the K-17 or K-22 cameras with 24-in. lens in both mounts), and (3) providing better damping action. The first peak in each case is that caused by the rotational resonance. For the case of the A-8 mount this is seen to occur at a much higher frequency than that dictated from considerations of best filtering action compatible with stability.

The A-11 mount presents a case of unusually poor damping control of the rotational resonance peak. The A-8 mount would also profit by better damping control, the action at present being more in the nature of a snubbing action rather than true damping.

The spring mount curve shows satisfactory operation in conformity with the established design principles.

1.6.5 Results of Flight Tests on Resolving-Power Targets

Table 12 gives the summary of results obtained in the comparative test of the first mount design with a standard A-8 mount.

The tests were carried out in an F-2 Beechcraft two-motor plane at Wright Field on July 15 and 16, 1943. Two mount supports were provided so that two cameras and two mounts could be used simultaneously.

Two K-17 cameras with 24-in., $f/6$ lenses were used in the test. One had a Bausch and Lomb lens which had been previously tested and focused at Kodak Park in Rochester, New York. The other K-17 had an Eastman lens and was not prechecked for focus. Super-XX film with No. 12 minus-blue filters was used.

Electric connections were made so that both shutters could be tripped together, either manually or by the sweep intervalometer of the Eastman mount. A standard viewer with 10-in. lens and ground glass was arranged to show when exposures should be made. Three pictures were made in each camera at each pass over the target, using the standard overlap of 60 per cent. The first and last shots placed the target approximately 8.5 degrees off the camera axis, while the middle shot was at approximately 0 degrees.

The altitude was 10,000 ft and the ground speed approximately 160 mph, resulting in an interval of approximately 6.5 sec.

Two passes were made for each of the sixteen possible combinations of mount location in the plane, camera, exposure setting, and sweep on or off. A few shots missed the target, but ninety usable pictures were obtained in each camera.

Following the aerial pictures, about eighteen ground pictures with each camera were made of a resolving-power chart at 386 ft, with ⅛-in. spacers behind the lenses. The cameras were placed horizontally on a sturdy table and the same exposures and angles were used as in the plane. The cameras gave nearly equal re-

TABLE 12. Results of flight tests on Eastman Kodak and A-8 mounts made at Wright Field, July 15 and 16, 1943.

Shutter speed (sec)	Aperture	Degrees off axis	No. of observations	Avg. resolving power (lines/mm) A-8 mount	EK mount	Per cent Improvement	Sweep for EK mount
			For lines parallel to flight				
1/150	$f/8$	0 and 8.5	46	7.07	7.26	2.7	
1/50	$f/11$-16	0 and 8.5	44	5.99	6.43	7.3	
			For lines perpendicular to flight				
1/150	$f/8$	0 and 8.5	23	6.56	6.84	4.3	off
1/50	$f/11$-16	0 and 8.5	24	4.00	4.13	3.3	off
1/150	$f/8$	0 and 8.5	23	6.52	7.50	15.0	on
1/50	$f/11$-16	0 and 8.5	20	3.97	8.59	116.4	on

solving power, averaging 10.8 lines per mm at $f/8$, and 11.7 lines per mm halfway between $f/11$ and $f/16$.

Table 13 shows the average resolving power for the 8.5-degree shots combined with the 0-degree shots. This gives predominance to the 8.5-degree shots since there were approximately twice as many, but it is felt that this is a fair estimate for overall picture quality.

The antivibration feature of the mount showed a consistent but small improvement. The sweep mechanism showed a definite and valuable improvement, particularly at $\frac{1}{50}$ sec exposure.

The Eastman-NDRC mount was observed to remove vibration from the camera to a marked degree, while for the A-8 mount the vibration appeared to be transmitted almost undiminished. This could be detected unmistakably by touching the camera or suspended parts lightly with the fingers.

The results were to some extent masked by the bad conditions of roll and pitch in the F-2 airplane.

Bedford Tests of Second Mount Design

On August 8, 1945, a test flight took place from the Bedford Army Air Field. Many of the conditions of the test were much more favorable than for the first test. A B-17 bomber was used; this proved to be quite stable with the air conditions prevalent, so that the factors of pitch and roll were much reduced.

A camera equipped with a Harvard-NDRC 40-in. $f/5$ telephoto lens was used for this test. This was equipped with a thermostat tempera-

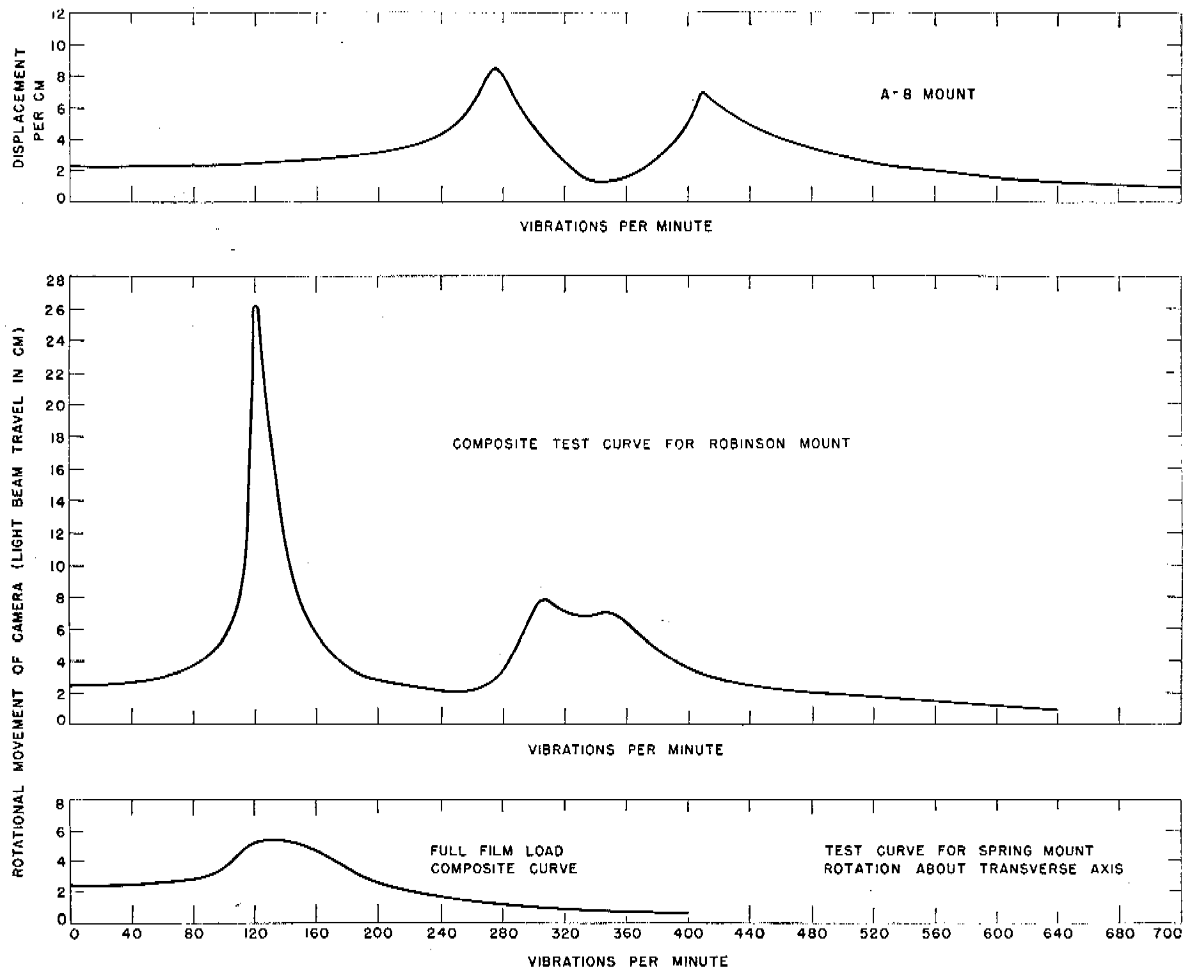


FIGURE 99. Test curves for A-8, Robinson, and spring mounts.

ture control and automatic focus, and had been checked on previous flights. One of the four mounts of the final design had previously been equipped with springs and sweep eccentric for this camera. Pan-X Aero film was used throughout the test. A number of individual readings gave a resolving power of 30.8 lines per mm. Thus the camera-film resolution in angular units was about 4.5 times that for the first test.

The test targets used were those constructed by Harvard on the abandoned air field at Orange, Massachusetts. Sensitometric checks on the film indicated a contrast ratio of 5/6 for the arrays of parallel-line test targets used.

TABLE 13. Results of flight tests of Eastman Kodak Model II mount and A-8 mount, made at Bedford, Massachusetts, August 8, 1945.

Shutter speed (sec)	Aperture	No. of observations	Mount	Avg. resolving power (lines/mm) Parallel	Perpendicular	Sweep for EK mount
1/150	$f/10$	48	A-8	18.2	5.1	
1/150	$f/10$	24	EK	21.1	5.6	off
1/150	$f/10$	14	EK	24.4	27.9	on
1/800	$f/5.6$	11	A-8	21.6	19.4	
1/800	$f/5.6$	9	EK	23.2	23.7	on

Most of the pictures were made at $\frac{1}{150}$ sec, $f/10$, with No. 12 yellow filter. The longer exposure time gives maximum emphasis to the motion factors. Some pictures were made at $\frac{1}{800}$ sec and $f/5.6$ with the No. 12 filter.

The altitude was 9,800 ft and the speed about 200 mph. The sweep interval was set at 3.0 sec. When the sweep was not used, the shutter was tripped manually by an electric connection at an estimated interval of 3 sec. An average of about eleven target images was thus obtained on each pass over the target with random positioning in the picture area. Ten useful passes were made.

Table 13 shows the average resolving power for lines parallel and perpendicular to flight and for each test condition as shown.

The use of the antivibration mount without the sweep mechanism improves the resolving power for lines parallel to flight by 16 per cent for $\frac{1}{150}$-sec exposure. The improvement is increased to 34 per cent for lines parallel to flight when the sweep is used. The low resolution for lines perpendicular to flight without the sweep has a definite influence upon the determination for lines parallel to flight; the lines are smeared out to a greater length thus affecting exposure and in some cases producing overlapping of charts.

The use of the sweep mechanism with $\frac{1}{150}$-sec exposure time improves the resolution for lines perpendicular to flight by 400 per cent over that obtained with the antivibration mount without sweep, and by 450 per cent over that obtained with the A-8 mount.

The magnitude of the overall improvement can best be judged by comparing 5× enlargements of the targets. Figure 100 shows one group of resolving-power targets and is representative of the average result obtained at $\frac{1}{150}$ sec with the A-8 mount. Figure 101 shows the same group of targets taken at $\frac{1}{150}$ sec with the antivibration mount with sweep working, and it is representative of the average for these conditions.

The crabbing angle was estimated at 5 degrees and adjusted accordingly at the time of the test. Later inspection of the negatives showed that this was too much adjustment. The effect is small but is greater for lines parallel than for lines perpendicular to flight. This, together with the fact that the roll effect is greater than the pitch effect, explains why greater resolution is obtained for the perpendicular lines than for the parallel lines.

At a shutter speed of $\frac{1}{800}$ sec, the antivibration mount with sweep shows an improvement of 22 per cent for the lines perpendicular to flight. The lines parallel to flight show an improvement of over 7 per cent. It is quite evident that the new mount with its sweep mechanism brings about a very worth-while improvement. The use of any high-resolution system, and especially those involving longer focal length lenses, should not be considered without the use of such a mount and ground-speed compensation.

ADDITIONAL FLIGHT TESTS

During the period from July to November, 1945, a number of both day and night flights were carried out from Bedford in connection

with the work at Harvard under Contract OEMsr-474.[10b]

In a large percentage of the day flights the Eastman-NDRC mount was used, and for the most part with the Harvard-NDRC 40-in. telephoto $f/5$ lens. These tests were not planned primarily to compare various mounts. However, very consistently high resolution was obtained on a number of flights (the highest being 41 lines per mm[10c] on Pan-X film).

The night tests were made to yield quantitative information on the amount and type of showed the Eastman-NDRC mount to be inferior to either the A-11 or A-8 mounts. Further analysis, however, shows that for the particular flights on which the Eastman-NDRC mount was tested the motions of the aircraft were considerably larger than for the flights on which the A-11 and A-8 mounts were tested. The average magnitude of aircraft motion was, in fact, greater by a larger ratio than the mount performance ratios. The data, while not conclusive, do indicate a margin in favor of the Eastman-NDRC antivibration mount.

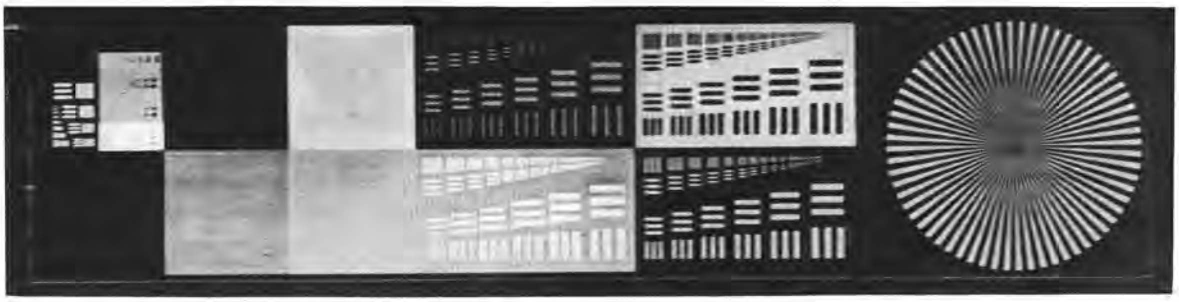


FIGURE 100. 5× enlargement of target, A-8 mount, 40-in. lens, 1/150 sec at $f/10$, Pan-X Aero film, No. 12 filter.

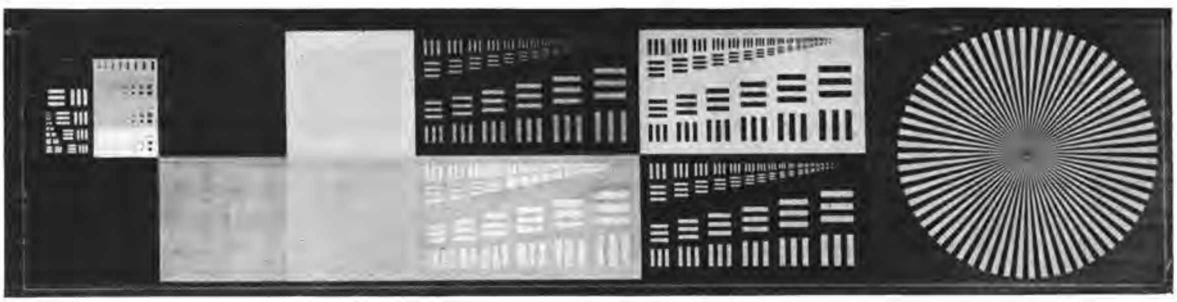


FIGURE 101. 5× enlargement of target, EK mount with sweep, 40-in. lens, 1/150 sec at $f/10$, Pan-X Aero film, No. 12 filter.

actual motion from the analysis of dot trails produced by flashing strobolux and neon lights. A number of other analytical test targets and devices[10d] were employed for both day and night tests.

In the analysis of night flight tests, all motions with periods shorter than 1 sec were arbitrarily ascribed to the camera-mount system, while only those with periods longer than 1 sec were ascribed to the aircraft. The summary tabulation[10e] of "average median angular velocities in mils/sec of the camera-mount system"

The frequencies of mount vibration[10f] as determined from the light trails by visual inspection are in line with what would be expected from the laboratory tests of the mounts. The Eastman-NDRC mount with few exceptions showed no frequencies higher than its natural frequency of 1.7 to 2.0 c. The A-8 and A-11 mounts showed higher frequencies ranging quite generally up to 12 c.

Earlier flight tests at Wright Field in the F5-E aircraft were also analyzed.[10g] Since the frequencies reported for the experimental

[redacted]

spring mount are well above the natural frequency for the suspension, there is good reason to conclude that the suspension was not free to function as intended.

The method of flash trail analysis is a powerful tool and can be made to yield much needed information. It is unfortunate that the reduction requires much tedious and time-consuming labor. The value for both design and test purposes would be very much enhanced if the analysis in the form of an amplitude-frequency spectrum could be quickly and accurately derived.

1.6.6 Center-of-Gravity Mount (Harvard)[10h]

Although almost every standard and experimental mount has approximated the condition that airplane forces imparted to the camera should pass only through the center of gravity, vibration studies indicate that no mount has succeeded altogether in this respect. In principle, if a camera is suspended at its exact center of gravity, no rotational forces can be imparted to change the direction of the optical axis. Translatory forces can only displace the optical axis by a negligible amount, as seen from the ground.

The application of the center-of-gravity principle assumes that the optical system within the support is a rigid body. In practice, such is not exactly the case. Residual translatory vibrations imparted through the precise center of gravity can set up vibrations within component parts of the camera system, and these in turn may affect the direction of the optical axis. For example, translatory vibrations might set up lateral vibration of a loose lens element, which in turn would shift the optical axis directly.

An attempt was made under the Harvard Contract OEMsr-474 to apply the center-of-gravity principle in detail and at the same time to provide for twin-mounted 40-in. telephotos that would give double coverage picture mosaics. Figure 102 shows a view of the apparatus developed.

The angle between the two telephotos has been chosen to give an overlap of ½ in. across the line of flight. The final mosaic therefore has a width of 17.5 in. The two telephotos are oriented, about a vertical axis, 90 degrees from the usual orientation of single cameras. This arrangement provides for opposed shutter re-

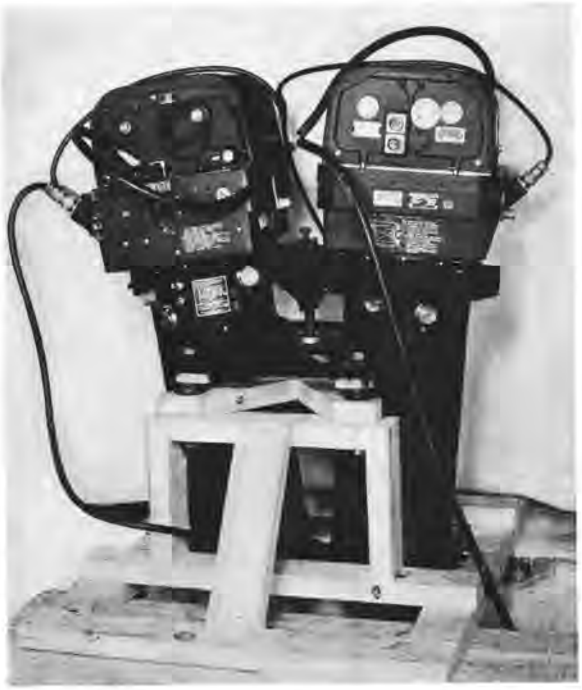


FIGURE 102. The center-of-gravity mount with two 40-in. $f/5$ telephotos.

coil within the two camera bodies, which in turn should eliminate the small angular recoil of the optical axis of a camera when a focal plane shutter is tripped, although it will not necessarily eliminate secondary vibrations imparted by release of the shutters. The cross mounting also permits equal and opposite film winding to preserve the exact center of gravity of the mount as a whole, as the film is used.

The entire 260-lb double assembly is suspended by a small steel ball (⅛ in. diameter) in a hardened steel cup at the exact center of gravity. The vertical adjustment of the center of gravity is obtained by a screw and lock nut. There is no arrangement provided for adjustment in a horizontal plane. Experience proved that such adjustment is highly desirable, and that small discrepancies in balance in the ab-

sence of restoring forces upset the alignment of the twin mount, which is analogous to the principle of weighing on an ordinary balance.

The center-of-gravity mount rested on a wooden truss, supported on sponge-rubber pads placed on the floor of the airplane. In this way translational vibration was reduced.

Flight tests on the program at Orange, Massachusetts, conducted at night over flashing neon lights proved that this center-of-gravity mount gave better performance than any other mount tested. With the 40-in. NDRC telephotos the center-of-gravity mount gave an angular velocity of 0.99 mils per sec in roll and 0.67 mils per sec in pitch from the average of four films, which is approximately one-half of the velocities given by the next best mount. These results were obtained in spite of the following points:

1. The lenses were procured from Army production and were not checked beforehand for tightness of lens elements in their cells. Since there are seven elements in each system, a slight looseness of one or more is probable.

2. The exact center of gravity was not achieved, since no adjustments in a horizontal plane had been provided, and since the power cables upset the balance in the plane.

3. An error in machining caused one camera to be off laterally by ⅛ in. in position. Balancing was accomplished by weights taped on in the best available places.

4. The lower ends of the cameras were clamped together by means of a protective thin felt separator, rather than by rigid contact, as would be desirable.

5. The lack of restoring forces makes it difficult to control long period motion in yaw. The off-center position of the cameras accentuates yaw difficulties. All steadying was done by hand, with residual linear motion.

6. The clamping of the adjustable screw for vertical center-of-gravity correction was misconstrued in the machining for easy fit. Consequently, the cameras were not rigidly connected to the center of gravity.

7. Each telephoto contains the automatic focusing unit, which controls the position of the rear element by spring and bellows. It is probable that the rear element will react to translatory vibrations imparted through the center of gravity, although all flight tests to date show no ill effects up to perhaps 30 lines per mm.

8. The observer was often forced to hold the mount steady for some moments by hand in order to overcome tilting caused by swinging cables and plane movement. On at least one flight the center of gravity was markedly below the point of support in a pendulous suspension through a misinterpretation by the observer at the time.

In spite of these eight points, the mount still gave the performance indicated above. All in all, it would seem that if the center-of-gravity principle were followed in all its exacting detail down to the last piece of metal, the vibration in angle would be almost entirely eliminated. Natural frequencies of individual parts of the apparatus should be watched with a view to minimizing angular effects of translatory vibrations through the center of gravity.

Daytime flight tests at Orange gave resolution results very much lower than those obtained with standard equipment. The results were so consistently low and so strongly at odds with the low vibration rates of the night flights that the conclusion must be drawn that the lenses were not in good optical adjustment in the air. The most probable explanation of the discrepancy is that the clamps provided for the individual lenses at the lower end, which are tightened by nuts at the time of installation by machinists in the plane, were drawn up entirely too tight. The 8-in. diameter elements are sensitive to strain. The wall thickness of the telephoto is about $\frac{1}{10}$ in. in the vicinity of the clamps. The resolution results were consistently lowest in the direction of flight, out of keeping with the average figures obtained from uncompensated mounts. The clamps would tend to produce maximum strain in the line of flight.

Later laboratory tests made with one of the lens systems proved that a resolution on Super-XX of 45 lines per mm could be obtained.

Discussion

Considerable effort should be put on the design and construction of a new center-of-gravity mount for general use. This mount

should incorporate soft restoring forces, quite possibly without damping, and by one means or another compensate for ground movement. It is evident that if angular vibration rates as low as 0.5 mils per second are obtained most of the time, and if ground movement is compensated, average resolution will remain at a level nearly equal to laboratory resolution in the presence of the haze encountered in the air, with the lens-film combination. Some attention should be given to activating the soft restoring forces by means of gyro control and servo mechanisms for maintenance of a good nadir. Careful attention should be given to the elimination of yaw.

If all the above points are carried out, it will prove possible to use longer exposure times and more efficient shutters, and what is even more important, to use slow-moving shutters that are unlikely to impart vibrations to the system.

1.6.7 Stabilized Aerial Camera Mounts

A thorough study was made at Eastman (Contract OEMsr-392) of the possible methods of stabilization control in cooperation with antioscillation control to obtain complete motion isolation from the camera. It was decided that the most promising method is that of developing the stabilization torque relative to gravity, that is, by shifting a weight or the camera itself relative to the suspension axis. This removes the burden of following large or rapid motions with the servo system and maintains at all times a center-of-gravity mount which is not susceptible to linear accelerations and permits a very low natural frequency for the antivibration suspension.

A further feature of the stabilization method as worked out is the provision of an "integrating" mechanism whose function is to compensate for the gradually accumulating film unbalance or other steadily applied torques without additional burden on the servo mechanism or the introduction of alignment errors.

A test model of the electromechanical follow-up mechanism was constructed and found to operate in complete conformity with the requirements. Further work would undoubtedly bring about simplifications and produce a model for flight tests.

Work was started on a stabilized mount utilizing an inertia-controlled mirror and having a very low natural frequency. The mount has a number of attractive features. No tests have yet been possible.

A stabilized camera mount using a different type of servo mechanism was developed by the Lawrence Aeronautical Corporation (Contract OEMsr-1366). See Section 1.8.6.

Eastman Servo-Controlled Stabilized Mount[26]

Introduction. It has been pointed out[25g] that it is not practical to place the natural frequency of spring-filtered aerial camera mounts much below 100 cycles per minute. This limit is set because of the shift of the center of gravity which results from the motion of the film in a camera, and also because of differences in location of the center of gravity in individual cameras. These effects make it impractical to maintain rigorously a center-of-gravity suspension under service conditions. It is thus necessary to keep the suspension springs sufficiently stiff so that alignment between the optical axis of the camera and the vertical may be maintained, and this results in a lower limit for the natural frequency. However, even with these limitations there is no doubt that the spring-type camera mount provides considerable improvement of aerial photographs, and there is reason to believe that further gains in resolving power could be made if mounts were available which would eliminate all disturbances including those of zero frequency. Such a mount would also maintain a certain orientation of the camera regardless of any shift of the center of gravity or motion of the airplane, a property which should be of considerable value in mapping operations.

Choice of Control Mechanism. Considering various possible control mechanisms, it is recognized that none is effective over the entire frequency range of possible disturbances, but that any of the possible devices operates best in a finite frequency band. The spring-mass type of filter becomes very unstable if it is used at

low frequencies; on the other hand, it is difficult to construct electromechanical follow-up or servo mechanisms which are effective at high speeds. It seemed therefore convenient for economical design to make use of both devices and to provide for sufficient overlap to cover the entire frequency spectrum satisfactorily. If F is the crossover frequency at which a spring-mass filter and the follow-up type of control should both be effective, it is judged that the natural frequency of the former should be not higher than $F/2$, and that of the latter not lower than $2F$. In view of previous experience with the two types of control, it was thought a good compromise to make F equal to 30 cycles per minute.

Design of Follow-up Mechanism. The purpose of the follow-up mechanism is to maintain alignment between the optical axis of the camera and a gimbalized gyroscope at a high degree of accuracy. The torques which tend to disturb the alignment, once it has been attained, are due to low-frequency linear acceleration forces and rotational torques of the airplane frame transmitted through the springs supporting the camera, and also to disturbances created within the camera by the motion of the film between exposures, acceleration forces of the shutter mechanism, air currents, etc. If the alignment between camera and gyroscope has been disturbed for some of these reasons, it may be restored (1) by driving the camera directly into the correct position through a motor attached to the airplane frame, (2) by generating restoring torque through compliant connections to the airplane, or (3) by applying restoring torque relative to space or gravity without reference to the airplane structure. The last alternative seems particularly attractive because it avoids mechanical connections between camera and airplane. These would add stiffness to or completely eliminate the benefits of the antivibration mount and thus transmit high-frequency disturbances. A further advantage is that mechanical motions of the correcting mechanism can take place relative to the stabilized platform itself rather than relative to the airplane frame. It becomes unnecessary then to compensate for possible large and rapid motions of the airplane by corresponding motions of mechanical members through which correcting torques are transmitted.

Of the several possible ways of applying torque relative to space, at least three merit consideration. The first makes use of a combination of cross springs and coil springs. The cross-spring structure has some positive stiffness and tends to oppose rotation of the frame, whereas the coil spring produces a torque that tends to pull it farther away from its rest position and thus supplies what may be called negative stiffness. The springs may be designed to produce stiffness of equal value but of opposite signs, and this results in a structure of infinite compliance. If, now, one end of the coil spring is shifted, it is seen that a torque proportional to the displacement is applied to the platform without reducing the compliance of the connection.

Another possibility is to make use of the reaction torque which is set up if a rotating flywheel is accelerated or decelerated. However, the torque obtained in this way is proportional to acceleration and it is not possible to maintain it for any length of time without reaching excessive flywheel speeds. The device is not suitable to compensate for static unbalance of the camera.

The last method, which was considered in connection with this work, produces restoring torque by moving a weight attached to the camera, or the camera itself, relative to the axis of rotation of the stabilized platform. Compared with the two other possibilities mentioned previously, this has the overwhelming advantage that any shift of the center of gravity occurring within the system is compensated for by rebalancing the camera. Thus, a center-of-gravity type suspension is continuously maintained, and an antivibration filter of very high rotational compliance (low natural frequency) may be used to effect filtering in the frequency range not covered by the follow-up mechanism.

For these reasons, the method of moving a weight was adopted to produce both temporary and continuous torques required to maintain alignment between camera and gyroscope axes.

General Layout of Stabilizer. At present only a laboratory model has been completed. This has

one axis of stabilization and uses brass weights in place of the camera. The contemplated arrangement of elements in a completed model is as follows.

To an inner gimbal ring which supports the camera is attached a gimbalized gyroscope with the spin axis vertical. Only a few degrees of angular motion need be provided in the gyroscope gimbal, which should preferably have cross-spring axes to avoid friction.

Two electric signals are provided by pickup elements at the gyroscope. These signals are proportional to the angular misalignment between the camera and the gyroscope with respect to the two horizontal axes of stabilization. With suitable amplification the signals operate two servo follow-up mechanisms, also mounted on the inner camera gimbal ring.

Either the camera may be given two degrees of freedom of horizontal linear motion with respect to the inner gimbal ring or the camera may be clamped rigidly to this ring and moving weights provided for the purpose of producing balancing torques. In either case the two servo mechanisms operate to shift the center of gravity to counteract any disturbances which would tilt the camera in space. Due consideration is given to the proper damping of oscillatory tendencies and to the balancing of permanently applied torques without burden upon the servo mechanism or the introduction of alignment errors.

The inner camera gimbal ring is to be supported by two small diametrically opposite compression springs. These perform the dual purpose of providing suitable antivibration operation for linear vibrations in all directions and of acting as one pivot axis of the gimbal. These springs offer extremely low rotational stiffness to camera motion, the natural frequency in rotation being in the order of 15 cycles per minute and well below the upper limit of functioning of the servo mechanism. These two springs are supported by an intermediate gimbal ring which, in turn, is supported by two more springs providing the other gimbal axis at 90 degrees to the first and also assisting in linear vibration control. The outer springs are supported by the airplane structure.

The gyroscope is preferably of the self-erecting type, but a neutral gyroscope may be used if a close approach to the true vertical need not be maintained and some recaging device is provided.

Because of the motion of the film between exposures, the center of gravity of the camera is shifting continuously. Some feature must be provided whereby continuous compensation torques can be maintained without requiring continuous input signals into the servo and hence continuous error of alignment. This is accomplished by an integrating mechanism which sums up the corrections applied by the mechanism and generates a torque equal to their time average, thus relieving the servo system from steady loads. The time constant of the integrator is chosen such that the error of alignment of the camera does not exceed a few minutes of arc at the highest rate of film motion required.

Design of Servo Mechanism. The first design[26a] made use of mechanical members to provide the functions of damping and integration as well as the direct displacement signal. The use of rotary viscous members employing Dow-Corning fluid in conjunction with various arrangements of springs, etc., made the method look very attractive. Only a comparatively small power output was required from the amplifier while the major portion of the work was to be done by a contact-actuated reversible motor operating directly from the 28-v d-c line.

Various arrangements of the components were tried and successful operation was obtained up to 30 cycles per minute. However, some trouble was experienced with friction and the pressure needed for positive contact operation. Servo motors with sufficient power for direct operation of the weight-shifting mechanism and with built-in generators for rate signals became available and proved to be more satisfactory although bigger amplifiers were required, lower electric efficiency resulted, and a balancing slide-wire bridge was required.

Figure 103 shows a schematic circuit diagram. A variometer V is used to detect misalignment, one coil being fastened to the gyroscope G and the other to the camera C. The signal generated in this way is added to the output of bridge B-1, amplified in channel N-1.

[redacted]

filtered in a band-pass filter *F*-1, and after further amplification, is fed into the control phase of a two-phase servo motor *M*-1. This motor drives a contact arm along slide wire *S*-1 of the bridge until it finds a position such that the output of the bridge cancels the signal delivered by the variometer. Since the shaft of the motor is also connected to the weight *W*-1, the loop in itself. Its natural frequency must be high compared to that of the overall servo in which the action of gravity on the weight *W*-1 supplies the restoring torque. A frequency of about 200 cycles per minute was found satisfactory. The damping of the minor servo loop just described is supplied electrically. A small induction generator *G*-1, located inside the

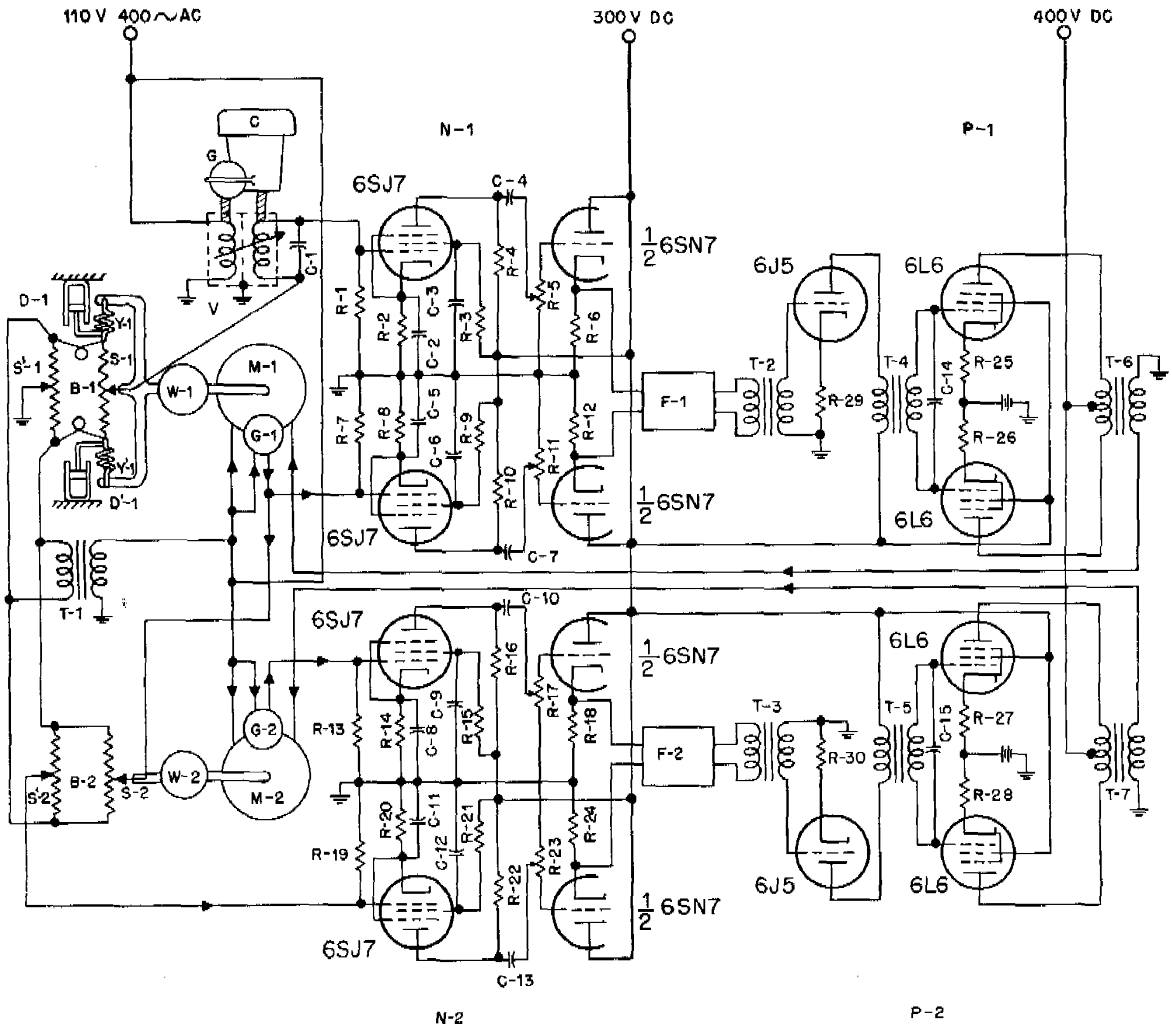


FIGURE 103. Schematic diagram of electrically damped servo.

weight is moved by a distance which is proportional to the angular displacement of the camera as measured by variometer *V*, and a proportional restoring torque is applied to the camera.

The circuit by which the position of the weight is continuously matched to the misalignment between camera and gyroscope is a servo shell of motor *M*-1, delivers a 400-c voltage proportional to its instantaneous velocity. This signal is amplified and added to the main displacement signal. The speed of the motor *M*-1 is proportional to the rotational velocity of the camera, and it was thought at first that the output of *G*-1 could also be used to generate damping torque for the major servo loop including

the camera. This is, however, incorrect for one loop when it is corrected for the other loop and, although the frequency at which damping is required is quite different for the two loops, none of the schemes to use the same signal proved successful. There are ways of overcoming this difficulty which are very promising. Owing to lack of time, a rather mechanically clumsy but otherwise straightforward method was chosen. This is shown in the lower half of Figure 103. The rate signal generated by *G*-1 is added to the output of bridge *B*-2, which is electrically similar to *B*-1. The resulting voltage is fed into an amplifier channel *N*-2, *P*-2, similar to that already described, and drives the servo motor *M*-2 until the voltage produced by *B*-2 matches the output of *G*-1. The weight *W*-2 is thus displaced, depending on the velocity of the camera, and generates a damping torque through gravity.

Damping of the second minor servo loop formed by generator *G*-1, bridge *B*-2, amplifiers *N*-2, *P*-2, and motor *M*-2 is done in the same way as described in connection with the first minor servo loop. The rate generator *G*-2 furnishes the necessary signal.

This system is wasteful of space and power because it duplicates all elements of the first servo loop. However, considering the short time available to finish up the project, and the experience that had been gained in constructing the displacement signal servo loop, it was thought best to proceed in this way.

The device employed to compensate for differences in mass distribution between individual cameras and changes, such as caused by the motion of the film in the camera, consists of springs *Y*-1, *Y′*-1, and the dashpots *D*-1, *D′*-1. The dashpots are filled with Dow-Corning silicone fluids which exhibit only a small change of viscosity with temperature. It is seen that for high-frequency motions of the contact arm of bridge *B*-1 the slide wire *S*-1 remains essentially stationary because of the stiff dashpots. If, however, some mass unbalance demands a new average position of the weight *W*-1, in order to level the camera, and thus produces a steady unbalanced signal in the servo, the springs *Y*-1, *Y′*-1 will eventually move the slide wire *S*-1 under the contact arm until the bridge is again balanced with the weight occupying its new position. Instead of moving *S*-1 a similar result could, of course, be obtained on the other side of the bridge by moving the ground point on *S′*-1.

A stable follow-up system that maintained the position of the dummy camera within approximately 1 min of arc and operated with a natural frequency of 60 cycles per minute has been built. A number of obvious improvements have occurred during the construction of the test model. The performance already attained is highly gratifying and indicates with a high degree of certainty that a completely satisfactory stabilized mount can be built. The elimination of the effects of all normal aircraft motions of any nature is assured.

Mirror Stabilized Mount[26b]

The sketch of Figure 104 illustrates a possible solution to the aerial camera stabilizing problem through the use of a mirror. Work was started on such a mount at the Eastman Kodak Company, but time did not permit completion.

The mirror, with its associated parts, is suspended by a pivot *A* at the center of gravity.

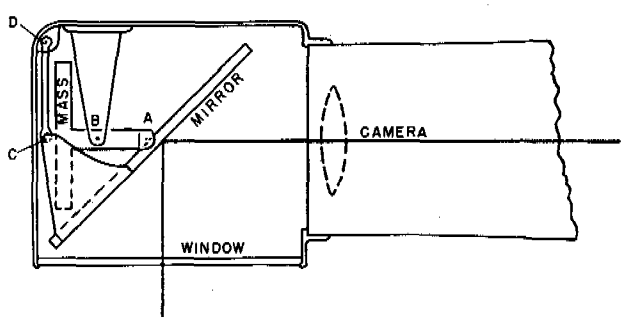


Figure 104. Schematic diagram of mirror stabilizer.

The linkage connection at *C* supports no weight. The mass is, in turn, pivoted at *B* just above the combined center of gravity of mass and mirror. The system is therefore pendulous and self-leveling. It is expected that the natural period of the pendulum or center of gravity arrangement can be made long compared to the 3- or 4-sec period of roll and pitch most commonly encountered. The point *C* is prevented from having up-and-down motion by the link running from *C* to *D*. For rotations about an

[redacted]

axis perpendicular to the paper, the mass essentially remains fixed in space, and the ratio of the distance AB to AC (essentially 1 to 2) is chosen such that the mirror is rotated through one-half the angle of the disturbance. The effect of the disturbance is therefore eliminated. For rotations about the optical axis of the lens, pivots B and C (having at least 2 degrees of freedom) allow both the mass and the mirror to be undisturbed.

While the natural frequency of such an inertia system cannot be made as low as that of a gyro system, it is believed that it can be made low enough for effective operation in view of the fact that the system is enclosed, free from air currents, and is not subject to shift of center of gravity.

The actual construction requires careful attention to rigidity and the elimination of play and friction at the pivots. It is expected that extensive use can be made of the spring hinge, which can be designed for ample rigidity and has no lost motion. The higher frequency motions can be eliminated by conventional antivibration means, thus avoiding the need of extreme rigidity.

It will be noted that the mirror causes a reversal of the image on the film. This means that contact prints (unless printed through the film base) are reversed left to right. Projection prints, enlargements, or contact transparencies (viewed through the back), however, provide nonreversed views and are, in general, to be preferred.

1.6.8 Ground-Speed Compensation Mount

Theory of Ground-Speed Compensation

The blurring effect produced by the forward speed of the airplane relative to the ground may be effectively eliminated if the camera is rotated in such a way as to cause the optical axis to pass through a fixed point on the ground during exposure. (The change of angular position and distance of ground objects relative to the camera are of secondary importance for the usual exposure time, speed, and altitude.) This method of compensation may be called the "sweep" method. There appear to be certain advantages of this method over other methods which may require optical complications and accurate moving mechanisms with attendant risk of deterioration of the optical definition.

The sweep mechanism may be conveniently combined with the functions of the intervalometer as the following equation[25h] shows:

$$v = \frac{3.6}{T},$$

where v is required compensating velocity (inches per second) of lens relative to the film for 9-in. film width and 60 per cent overlap, and T is picture interval in seconds.

Since the required velocity of lens relative to film is dependent only upon the interval T, it follows that the sweep mechanism may be automatically set without further adjustment when the intervalometer is properly set.

The sweep mechanism may impart any suitable movement to the camera as long as the proper velocity is imparted during exposure and the camera returned to the initial position so that the cycle may be repeated at an interval (or subinterval) of T seconds. The duration of exposure is extremely short compared to the interval T, so that a sinusoidal movement is entirely adequate if exposure takes place at the mid-position of the backward sweep. For a lens of 24-in. focal length, the angular amplitude of the sweep motion is fixed at 1° 22′ or a total sweep angle of 2°44′.

Details of Sweep Mechanism. The theory of ground-speed compensation serves as an indication of what the general design should be. Exact details are less important and depend upon many factors, such as expediency and preference. The box housing the sweep mechanism of the Eastman-NDRC mount is shown in the photograph of Figure 96.

The mechanism is mounted on the trolley arrangement of the crabbing adjustment rolling on the outer ring of the A-8 mount and moves the inner carriage on its transverse pivot axis. Very nearly sinusoidal movement is imparted through an eccentric and connecting rod arrangement. The connection between the lower end of the connecting rod and the inner carriage is accomplished through a lever arrangement providing a smooth leveling adjustment about the transverse axis.

The upper end of the connecting rod is driven by a crank shaft which makes one revolution during the time interval between pictures. The eccentric is easily changed on the second design to permit different per cent overlaps or different camera and lens combinations.

The gear on the eccentric shaft carries a fiber button. This actuates a set of contacts to perform the functions of tripping the camera shutter at the proper time and of stopping the sweep motor only when the camera is in the level position after the manual off-switch is thrown. A short length of cable is connected permanently to the sweep mechanism and plugs into the camera in the usual intervalometer connection without alteration of wiring.

The speed of the sweep motor is controlled and adjusted by means of a mechanical governor in which the centrifugal force pulls a rotating disk against stationary adjustable fiber buttons. A range of from 3 to 20 sec of time interval is covered in the final design. Still shorter intervals can be easily accommodated by a change of gears which would also shorten the maximum interval correspondingly.

FIGURE 105. The rotating prism compensator.

The use of the sweep mechanism on numerous flight tests has thoroughly proved its effectiveness and its complete practicability. In some cases, as large as 400 per cent improvement[251] at $\frac{1}{150}$ sec exposure, 10,000 ft altitude, and 200 mph speed has been obtained. In fact it is quite probable that such a ground-speed compensating device represents the only single improvement that yields such large results in proportion to the amount of expense and effort required.

The strongest possible recommendation should be made to incorporate ground-speed compensation into standard photographic equipment.

Summary. Compensation by the method of swinging the camera about the transverse axis was incorporated into the antivibration mounts. The correct sweeping rate is automatically obtained when the picture-taking interval is manually set. Highly satisfactory results were obtained on flight tests showing 400 per cent improvement in resolving power at $\frac{1}{150}$ sec exposure and 10,000 ft altitude.

ROTATING PRISM UNIT (HARVARD)[101]

Several independent investigators have suggested the possibility of using rotating low-angle prisms below the aerial camera for the purpose of eliminating ground movement of the image. In order to obtain to-and-fro harmonic oscillation of the image in the line of flight, it is necessary to use two identical prisms, which at the moment of exposure are moving in opposite directions and have zero deviation and therefore zero color. The important thing is not the deviation but the rate of change of the deviation.

The idea was put into practice under the Harvard contract. The end of World War II prevented completion of the device in the form of a workable and producible unit, but enough was accomplished to prove that the method would work satisfactorily if fully developed. The prisms are always moving at constant rates and therefore will not impart accelerations to the camera.

Figure 105 shows a view of the unfinished rotating prism unit built at Harvard. The report states that some of the engineering details require review and that haste engendered by the end of World War II forced use of improper materials.

The elementary theory of this device is presented in the Harvard report. The prism angles turn out to be very small, in spite of the rela-

[redacted]

tively long period of rotation. If 60 per cent overlap is desired, the variation in thickness of a single prism is given by

$$w = \frac{0.9}{(n-1)} \frac{d}{f}$$

where d is the diameter of the prism and f the focal length of the lens. For a crown-glass prism of BSC-2 glass used with a 40-in. lens at $f/5$, the prism angle is given by a variation in thickness of 0.113 in. or an angle of 0.00716 radians.

In the mounting, each prism is set at minimum deviation in its cell. Thus, vibration of the prism will cause almost no displacement of the image, particularly since the deviation is already small. It is believed that the prism pair together are extremely insensitive to constructional errors of any ordinary kind, although the optical quality must be excellent.

The preliminary tests of the Harvard unit showed erratic rotation, caused by a flexible drive between the power unit and the prism device. It was thought inadvisable to mount a drive on the camera itself. Figure 105, which shows a driving motor on the prism unit, was made during preliminary tests which were interrupted by the end of the project. Plans were under way to make use of the variable speed drive manufactured by the Chicago Aerial Survey Corporation.

The timing of the prism unit exposure takes into account the delay of a focal plane shutter in moving across the film. The timing is so set that the prisms are in their ideal zero deviation position on the only linear portion of the harmonic oscillation at the moment when the slit of the focal plane shutter reaches the middle of the picture at a 3-sec interval, with high tension K-22 shutter.

Although the rotating prism device is capable of eliminating ground movement without deleterious effects on vibration, focus, or color correction, it is believed that such a solution in the long run is not advantageous. The presence of four extra glass-air surfaces, even though coated, creates additional scattering and loss of light. The British found that lens coatings were very ineffective on lenses that had been in service long enough to have all lens surfaces somewhat soiled, and that the gain from coating was not comparable to losses from dust and grease. Since the prisms are in an exposed position, relative to internal lens elements, it is probable that the loss of efficiency will be felt very quickly. Probably the device should be regarded as primarily of experimental character to ascertain in flight testing the effects of compensation on resolution, and as a guide to tolerances on moving film or mechanical sweep methods. All in all, it would appear that a perfected sweep mechanism is the most nearly ideal solution to the problem of image movement compensation.

1.6.9 Gun Camera Antivibration Mounts[27]

Antivibration mounting techniques have been worked out for mounting the gun camera as a single unit and in combination with a gunsight to record the reticle image as well as the target. The laboratory tests show highly satisfactory performance for the single unit, and very encouraging results from the camera-sight combination for which all the antivibration effects are produced by a small detachable and self-contained mirror unit next to the camera lens. Even better results are expected from this unit with further development. High-speed motion picture studies were made on two Martin upper-gun turrets to establish the requirements for camera mounts and to guide in shake-table tests.

The development work on this project is divided into two parts. The first part deals with gun-camera mounts for fixed gun installations. The second part deals with flexible gun installations for which lead computing sights are used. The standard gunsight aiming point camera [GSAP] was used for both installations.

Theoretical Considerations

In considering picture blurring, only two components of motion are of prime importance. These are the rotational components about the vertical axis and the transverse axis of the camera as it is normally positioned with horizontal optical axis. The three translational components of movement, as such, have no practical effect upon the picture blurring. If the mount

is arranged so that the forces of acceleration set up by the translational components act effectively at the center of gravity of the camera, they can then introduce no rotational movements.

There are, however, three chief advantages to be derived from also providing filtering action against translational vibrations of appreciable magnitude: (1) The stresses set up in the mount and camera mechanism are greatly reduced and these parts are thus protected. (2) Rotational movements caused by lack of rigidity of the mounting bracket or panel, particularly at its natural frequency, are reduced. (3) The strict requirement that translational acceleration forces be applied effectively at the center of gravity of the camera is relaxed to the extent that translational vibrations are filtered out. The translational vibration along the axis of the gun is likely to be of very considerable magnitude.

Vibration filtering action is accomplished by the camera mass in cooperation with a mounting of adequate compliance. The lower the natural frequency of the mount in comparison with the disturbing frequency, the more effective is the filtering action. The natural frequency must not be made too low because of practical considerations of stability. Individual circumstances differ, but 100 cycles per minute has been found to be a practical lower limit.

Disturbing frequencies lower than the natural frequency are not filtered, while those near the natural frequency may actually be magnified many times. It is the function of the damper to control the amplitude for frequencies near the natural frequency. This function is essential for proper behavior to transient disturbances, even if no steady disturbance near the natural frequency is present.

Dampers employing viscous fluids are objectionable for reasons of structural complication, change with temperature, and possible leaks. Air dashpot dampers are also structurally complicated, are subject to clogging or air leaks, and often contain delicate parts. The employment of simple friction for damping offers advantages of extreme simplicity, adaptability of design, adjustment, etc. In some cases ordinary sleeve bearings may be used in place of antifriction bearings, thus simplifying and making the design more rugged, while providing proper damping. For frequencies above the natural frequency, the action of the damper is detrimental to filtering action since the damper affords a coupling between the support and the camera through which some disturbing force can be transmitted. The force provided by a simple friction damper is practically independent of velocity, while that provided by a viscous or equivalent damper increases linearly with velocity. It follows, therefore, that the viscous damper is more detrimental to filtering action since the velocity of motion is greater at the frequency of filtering than at the natural frequency for a given amplitude of disturbance.

The objection of inadequate boresighting may be raised for the friction damper. This is the case since the camera may come to static rest at any angular position within a finite zone determined by the amount of friction and the stiffness of mounts. The magnitude of this zone is, in fact, a sufficient measure of the damping effect and must not be too small if the damping is to be adequate. For the gimbal mount as submitted, the static angular friction zone is approximately 10 mils wide (± 5 mils from the mean position). In making shake-table tests it was discovered that the dynamic boresighting always remained within 1 mil. It is hoped that engine vibration in the airplane will alone suffice to maintain this accuracy. In any event, the gun firing will quickly establish the proper camera alignment.

There is another source of boresighting inaccuracy which is quite independent of the type of damping or mount structure. This is the unbalance produced by the movement of film from supply to takeup reel. For the gimbal mount as submitted, the misalignment is approximately ± 8 mils of angle about the transverse axis for 30 ft of film. The natural frequency about that axis is 115 cycles per minute. By increasing the natural frequency, the misalignment can be reduced at the expense of the filtering action. A compensating weight could also be employed if the refinement warrants the complication.

Boresighting is accomplished in the gimbal mount by the simple expedient of releasing the

compliance springs and clamping them again when the camera is properly aligned. This assures that the alignment comes at the center of the static friction zone. No vibration need be present when boresighting is done.

Gun Camera Spring Mount

The spring mount idea proved to be a good solution to the aerial camera mount problem.[25j] For this reason a compact design was worked out for the first trial mount of the gun camera. A center-of-gravity mount was achieved with filtering action for all six components of vibration. A number of factors combined to make this a less attractive solution to the gun camera problem. The translational natural frequency of a spring and mass combination is a function of the static deflection of the spring when the mass is placed on it. This is true regardless of the actual size or weight of mass involved. The proportion of deflection to size is therefore larger for the small mass. The gun camera must function for a wide range of angular attitudes of the airplane, while the aerial camera functions only in level flight. These facts required the size of the filter units to be larger than desirable; also the natural frequency could not be as low as desired.

Gun Camera Gimbal Mount

The center of gravity of the gun camera moves comparatively little with the shift of the film in the magazine (approximately ± 0.019 in. fore and aft for a 30-ft roll). This makes the gimbal mount quite feasible even if all translational components are not removed. The weight of the gun camera is such that plain gimbal bearings of adequate strength do not present too much friction for damping purposes. This avoids the necessity of using ball bearings and makes for a simple, compact, and rugged mount.

Figure 106 shows the camera in one possible mounting position in the gimbal mount. The trunnions forming the gimbal axes are adjusted according to the center-of-gravity location. The small springs provide the restoring torque and establish the natural frequency about each axis. Longitudinal filter action is obtained by suspending the intermediate carriage with four parallel arms. The parallelogram arrangement avoids any possibility of longitudinal motions introducing rotational motions to the gimbal. The pivot arms are $\frac{3}{4}$ in. long, which gives a pendulum effect with a natural frequency of 216 cycles per minute. Rubber stops are provided as safety limiters for rotation about each gimbal axis. None are required for the longitudinal filter system.

Gimbal Mount Performance

Figures 107, 108, and 109 show enlargements of pictures taken at 16 frames per second with the gun camera in the gimbal mount on the laboratory shake table. The shake table was not in operation for Figure 107 but was providing the following disturbances at 800 cycles per minute for Figures 108 and 109: (1) 8.1 mils total angular rotation about transverse axis, (2) 0.023 in. total translational movement along vertical axis, and (3) 0.026 in. total translational movement along longitudinal axis. The mount was blocked in such a way that no filtering action took place for Figure 109.

It is felt that this mount demonstrates adequately the soundness of the principles upon which it was constructed and provides a basic solution of the gun camera antivibration mount problem.

Camera Mount for Flexible Gun Installations

The problem of mounting a gun camera in conjunction with a sight to obtain a combined reticle and target image which is not blurred is evidently quite involved. The normal functioning of the sight must not be affected, the vision of the gunner must not be obstructed, and it is necessary to adhere to the rigid space limitations.

The K-15 (Mark 18) sight was used in this phase of the camera mount project. Preliminary to the actual mount construction, exhaustive tests of motions in the Martin upper turret[27a] under firing conditions were made with the aid of high-speed photographic equipment. These were carried out at Patuxent River, Maryland, in November 1944, and at Wright Field in February 1945.

The tests showed that filtering action about

both the transverse and vertical axes must be provided and that it would be desirable to obtain a 10/1 reduction in amplitude at the firing frequency and higher frequencies.

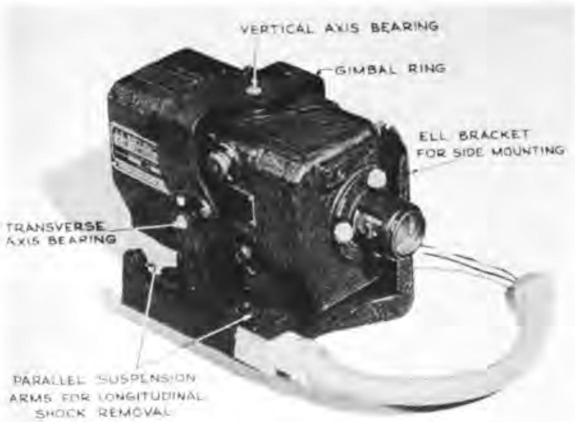


FIGURE 106. Gun camera gimbal antivibration mount.

Antivibration mounting of the sight plus camera as a unit does not seem feasible because of the necessity of bringing in the range cable with its stiff tension spring, the rather

FIGURE 107. Gun camera pictures made in gimbal mount without disturbance from shake table, 16 frames per second.

stiff electric cable connection, the necessity of strict boresighting, and the space limitation. A better approach seems to be to locate the camera in such a position that a clear picture of the target may be obtained regardless of the motions of the sight. The reticle image then has some motion, but about 70 per cent of this is removed by the action of the gyro mirror. It is difficult to find a suitable location because of limited space and limited possible locations. The most promising approach appears to lie in the direction of antivibration mounting of one of the mirrors required for relaying the images to the camera, preferably the mirror next to the camera. The camera is then rigidly connected to the sight and the compact mirror mount can be more advantageously located and protected by an enclosure with none of the worries of

FIGURE 108. Gun camera pictures made in gimbal mount with 800 cycles per minute disturbance from shake table, 16 frames per second.

shifting center of gravity, electric connections, or ruggedness of design.

The most promising location of the standard gun camera, from the standpoint of available space in the turret and functional operation, and with minimum vision obstruction, seems to be at the right side of the sight (as seen from the gunner's position) with the optical axis pointing upward and parallel to that of the reticle collimating lenses. This is shown by the photographic view of Figure 110. It is seen that the light is relayed into a small enclosure above the camera lens by means of a 45-degree fixed mirror located above the combining glass on the lead computing side of the sight. Another 45-degree controllable mirror is located inside the enclosure to direct the light down into the camera. The normal combining glass

is replaced by one with a 45 per cent reflection coating. The camera may be released and rotated to the horizontal position for purposes of loading the film.

As indicated previously, the mirror just above the camera lens must be controlled in such a manner as to remove the effects of angular vibration. This is the only vibration control in the system since the camera is rigidly connected to the sight and no alteration is made in the connection of the sight to its supporting yoke. Obviously, the desired result cannot be obtained by antivibration mounting of this mirror directly. The mirror can, however, be made to execute the required motions by suitable

FIGURE 109. Gun camera pictures made on shake table with filtering action of mount blocked out. Same 800 cycles per minute disturbance as for Figure 108.

linkage to a mass which is antivibration mounted and essentially functions as a fixed reference.

Figure 111 shows the camera lens with the antivibration controlled mirror.[27b] The natural frequency about the transverse and vertical axes is approximately 150 cycles per minute, and dry-friction damping is employed. The unit is unaffected by air currents or accidental contacts, is replaceable as an interchangeable unit, and is quite rugged. The mirror arrangement is such as to reverse the picture left and right. This effect is eliminated by turning the film over in projecting or assessing.

The mirror mount was tested by placing the entire sight and camera unit on a shake table and taking pictures while it was in operation. The table was adjusted to provide a rotational amplitude of 10 mils about both the vertical and transverse axes simultaneously (circular-type motion) and at a frequency of 800 cycles per minute. The turret tests show that this 20-mil total angle of vibration is typical of actual conditions. With perfect filtering action, as regards the target image, the reticle image still retains 30 per cent of the original motion owing to the action of the gyro-controlled mirror in the sight. The picture quality shows a substantial improvement in comparing pictures made with the antivibration mirror with those made when a fixed mirror is substituted. It is felt, however, that the mirror mount operation is not as good as might be expected and that it can be improved further.

1.7 SHUTTERS FOR AERIAL CAMERAS

During the course of World War II a number of projects were initiated for the purpose of improving the speed and efficiency of shutters for aerial cameras. Most of this work was confined to between-the-lens or louvre shutters. No NDRC work was carried out on focal plane shutters, with the exception of the multiple slit focal plane shutter described below. Valuable work was accomplished elsewhere on focal plane shutters, particularly near the end of World War II.

1.7.1 The Improved Metrogon Shutter[28]

The standard Metrogon shutter for the 6-in. Metrogon lens provides a least exposure time of $\frac{1}{300}$ sec. The Mount Wilson Observatory was requested under Contract OEMsr-101 to decrease the exposure time, if possible, to $\frac{1}{500}$ sec without marked change in shutter efficiency.

Investigation showed that 97 per cent of the inertia of the moving parts of the shutter arose in the activating cam, whose mass and bearings were not favorable for fastest operation. A slight contribution came also from the shutter blade assembly.

By machining the entire activating cam of

much reduced weight from a single piece of metal as permitted by the forces acting, it proved possible to reduce the total moment of inertia by more than threefold. After several experiments on types of material for the cams, it was found that the best material was steel, carburized deeply at the ball races, but only lightly over the rest of the surface.

Figures 112 and 113 show comparative views of the new and old cams, both disassembled and in position. The new cam weighs less than half as much as the standard cam, and its moment of inertia is reduced by a factor of 3.3. This results in a decrease in the exposure time by a factor of about 1.7, or nearly $\sqrt{3.3}$, as might be expected if the cam is the limiting factor.

Other slight changes in design were carried through to aid in the effective operation of the new-type cam and to add to the life of the assembly. It is stated that the total time taken to replace the standard parts by the ready-made modified parts is about 2 hours.

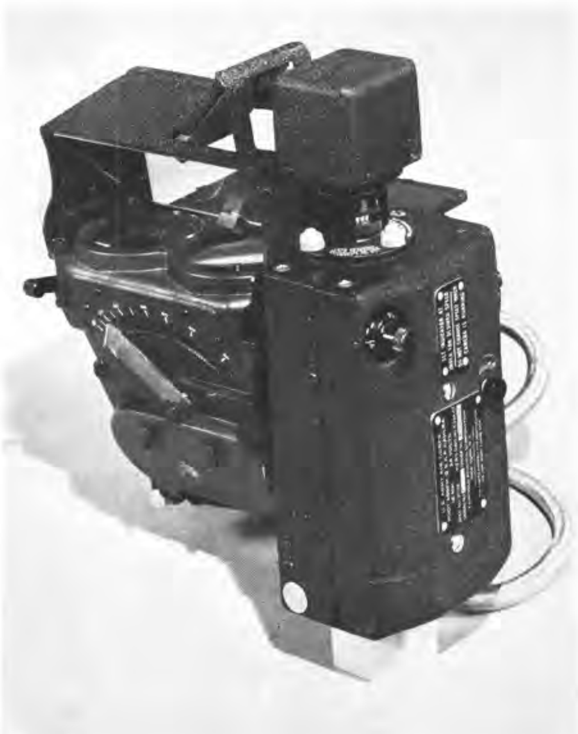


FIGURE 110. Gun camera attached to K-15 sight.

FIGURE 111. Antivibration controlled mirror of gun camera mount.

Performance. The shutter speed and efficiency curve were determined by means of a photocell and oscilloscope with photographed traces. These observations showed that at the peak speed, performance is satisfactorily uniform from one shutter to another. All modified shutters tested proved to vary in a total range of 10 per cent, with an average exposure time of $\frac{1}{460}$ sec. The efficiency of the modified shutter proved to be 77 per cent, leading to an effective exposure time of $\frac{1}{570}$ sec.

Table 14 reproduces observed data on one of the modified shutters.

Table 15 shows values of the total exposure times for three modified shutters at each of the four available settings.

Durability. No systematic breakdown tests were performed at Mount Wilson. Two of the shutters, however, were run two or three thousand exposures each, with cams from the first group made up. Cams from a second group were installed in five cameras, and each of these

was operated about 300 exposures without any indication of wear or breakage.

Discussion. It was believed at Mount Wilson that the modification of the 6-in. Metrogon shutter was one of the most important accomplishments under Contract OEMsr-101. Several improved units were used on important missions in Italy. These improved units led to a redesign of the standard unit for later production. The success achieved also set a pattern for other types of shutter work.

TABLE 14. Observations on speed and efficiency of improved Metrogon shutter.

Shutter setting (sec)	Dot frequency	Number of dots	Total exposure (sec)	Effective exposure (sec)	Efficiency (per cent)
1/300	5,000	11.0	1/455	1/590	77
1/225	2,500	7.3	1/340	1/450	75
1/100	2,500	14.2	1/175	1/200	88
1/50	1,250	22.0	1/57	1/61	93

TABLE 15. Total exposure time (sec) at four settings for three modified Metrogon shutters.

Shutter setting (sec)	Shutter serial number		
	1684	1607	1643
1/300	1/455	1/450	1/475
1/225	1/340	1/270	1/245
1/100	1/175	1/120	1/167
1/50	1/57	1/65	1/60

1.7.2 The Improved 24-in. K-17 Shutter[29]

Following the successful modification of the 6-in. Metrogon shutter, work was initiated under Contract OEMsr-101 on similar improvements for the K-17 between-the-lens shutter for the 24-in. standard aerial lens.

Whereas the study of the Metrogon shutter had revealed the cam to be a major limiting factor in speed, analysis of the 24-in. shutter showed that neither the cam nor the blades could be singled out for improvement. In addition to a general improvement, it was believed that the most promising method of increasing the speed involved replacing the driving spring by a more powerful driving system.

A triple spring was developed which can be installed readily, and which reduces the total exposure about 30 per cent. It was considered doubtful that the shutter blade assembly could withstand such an increase in speed for long, and that development of improved materials and construction was indicated. No work was accomplished along these lines.

The triple spring system developed in prototype comprised three 10-coil springs, each with a single winding. The driving torque was thereby tripled, relative to the standard 30-coil, 2¾-turn spring drive, and the moment of inertia very much reduced. However, the total gain in speed was about 30 per cent, limited by the inertia of the other moving parts.

Performance. Figure 114 shows a comparison of three shutter drives as described. Table 16 reproduces observed shutter speeds of the various drives.

Discussion. Only about one-third of the total effective inertia of the system is due to the shutter blades. It was believed that any work on improved shutter blades should be in the direction of greater strength and durability for the same moment of inertia. A beryllium-aluminum alloy is recommended.

An improvement in the cam similar to that found useful in the 6-in. Metrogon shutter would lead to an increase in shutter speed of only 15 per cent. Other improvements all along the line in bearings, spring clip, and safety collar, together would lead to a slight increase in shutter speed.

It was believed that flutter of the shutter blades might deflect the blades at the center of the exposure out of line and thereby retard the closing action. Metal guides were added to restrain the open leaves to one plane. A prototype showed no improvement, however, in shutter speed.

Durability. Two new K-17 shutters were modified by means of the 10-coil triple spring drive. No other changes were made.

One of the shutters was operated a total of 2,725 exposures, the other 225. In both cases the tests were stopped when the shutter blades cut into each other on closing, a frequent cause of breakdown of the standard shutter.

The bearings of the operating links showed

noticeable wear in the first of the shutters, but this fact did not prevent satisfactory operation. Other parts of the shutter assembly and camshaft showed no evidence of unusual wear.

Some difficulty was experienced with failure of the shutter to release. This failure is followed immediately by a further winding of the spring, which results in the breaking of a pin in the camera, necessitating repair.

FIGURE 112. Left, new cam with bearing assembled. Center, new cam, including spring connector. Right, standard cam.

In conclusion, although the triple spring itself can be installed very simply, it probably cannot be used successfully without further changes in the assembly. The tests that have been made indicate that these changes include a minimum strengthening of the tripping mechanism and some modification of the shutter leaves, which will prevent breakdown. The shutter-blade links and their bearings may also need strengthening.

1.7.3 The Multiple Slit Focal Plane Shutter

Under Project AC-29, NDRC was asked to develop a multiple slit focal plane shutter of the type proposed by Langer in the hope that distortion, nonuniformity of exposure, and limited life ordinarily associated with focal plane shutters might be reduced.

The proposed type of shutter took on two forms. The first of these was developed at the Mount Wilson Observatory under Contract OEMsr-101,[29a] and the second at the Technicolor Motion Picture Corporation under Contract OEMsr-710.[30] Both types of shutter produce the exposure by moving a primary screen with parallel slots. A secondary screen with wider slots, but the same center to center spacing, protects the film from light fog, before and after the exposure, and moves during the exposure in such a way as to permit light to pass through slots in the primary screen.

There is inevitably a narrow strip at the boundary between the regions exposed by adja-

FIGURE 113. Shutter housings, with blade assembly and connecting link removed. Standard cam in position at left, new cam at right.

cent slots which receives exposure from both slots. Although the time interval between the two exposures can ordinarily be held below 0.001 sec, perceptible doubling of the image may exist in these boundary regions. The combined area over which this doubling can occur can be held to less than 10 per cent of the total area of the photograph, and in any case the doubling is noticeable only when image motion is considerable. It should be noted that blurring of almost the same amount occurs over the entire photograph with present between-the-lens shutters operating at $\frac{1}{150}$ sec. Actually, doubling may be preferable to blurring, since it has less effect on recognition of detail.

The two types of multiple slit shutters differ in their mechanical motions.

THE LANGER SHUTTER

The primary and secondary slotted screens are linked together and travel with a fixed ratio of speed (approximately 2/1). As a result, the film is uncovered gradually, and there is a region of appreciable width within which there is double exposure. The mechanical linkage is very simple, and strips of uneven density can

easily be reduced to an unobjectionable level by contact printing through a compensating screen.

TABLE 16. Observed shutter speeds.

Drive	Total exposure (sec)	Effective exposure (sec)	Efficiency (per cent)
Standard spring and winding	0.0067 or 1/150	0.0044 or 1/230	66
10-coil spring wound 1 turn	0.0071 or 1/140	0.0048 or 1/210	67
wound 1⅓ turns	0.0062 or 1/160	0.0042 or 1/235	68
8-coil spring wound 1 turn	0.0071 or 1/140	0.0051 or 1/195	72
Triple spring 10-coil wound 1 turn	0.0048 or 1/210	0.0035 or 1/285	73
wound 1⅓ turns	0.0043 or 1/230	0.0032 or 1/310	74
Triple spring 8-coil wound 1 turn	0.0050 or 1/200	0.0036 or 1/280	72

Type 1. Analytically, the simplest arrangement is for the secondary screen to be held stationary while the primary slots are being uncovered and again while they are being covered. Figure 115 shows the situation schematically at selected moments during an exposure. At the right of Figure 115 is given for each position the distance that each screen has moved from its initial position (1) and the time elapsed since the start of the exposure when the screens were at (2). The shaded areas below the line indicate the amount of exposure at each point on the film from the beginning of the exposure until the moment illustrated. To the left of the heavy broken line is shown the ideal case in which all light is incident normal to the film. To the right of the broken line is indicated the more realistic case of a lens of $f/3$ aperture.

It is clear that for this motion of the screens the area of overlap is caused entirely by the finite solid angle subtended by the lens at the film. The width of overlap is proportional to lens diameter, and to the distance h of film screen, and is inversely proportional to focal distance. It does not depend on dimensions of either the primary or secondary slots.

Type 2. In Type 2 the secondary screen is in uniform motion. Construction of the operating mechanism is simplified in this case, provided the screen velocities have a fixed ratio. Figure 116 shows the progressive exposure effects of this type of multiple slit shutter.

Although motion in Type 2 gives more overlap than Type 1, there are considerable practical advantages involved. Since the screens are always positively linked together, a single source of power is sufficient, and there is nothing to cause irregularity in the motion. Once the blades are correctly assembled on the lever system required, there is no reason for their getting out of adjustment. If errors of adjustment do occur, they cause less noticeable exposure differences in the regions of overlap than do equal errors with motions of Type 1.

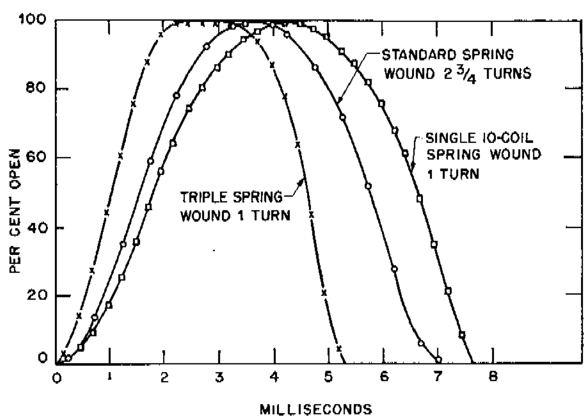


FIGURE 114. Shutter tests—comparison of springs.

Figure 117 shows a prototype of Type 2 constructed at Mount Wilson. The shutter is intended to cover a film 6¼x8¼ in., the slots running the short dimension. The eighteen slots in each screen are 6¼ in. long and have a spacing between centers of $d = ½$ in. The width w_p of the primary slots is $1/16$ in. and that of the secondary slots w_s, ¼ in. The screens are 7¾x10¼ in. in size and are of Duralumin sheet, 0.015 in. thick.

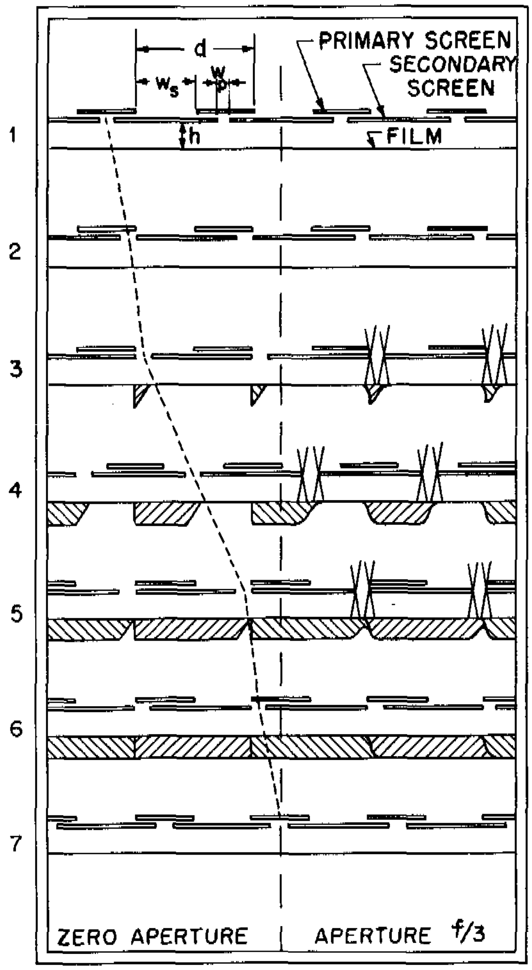
The shutter is driven by a coiled spring, exerting a force of 12 lb at the beginning of the stroke. To give an effective exposure time of 0.001 sec, the velocity of the primary screen

must be 62.5 in. per sec, reached by a uniform acceleration of 870 ft per sec^2 (27 g).

Figure 118 reproduces a typical photograph, made with a Cooke Aviar of 20-in. focus at $f/5.6$. The automobile was moving at 30 ft per sec at a distance of 120 ft from the camera, corresponding to ground-speed motion of a plane flying at 1800 ft altitude at 300 mph. The exposure of 0.001 sec was fast enough to stop the motion, although imperfect focus prevented the test from being critical. The doubling of the image is seen at the lower edge of the front mudguard and the upper edge of the windshield.

In judging the importance of this doubling it should be remembered that (1) it is roughly 15 times as great under the conditions of the test as in normal aerial photography, (2) noticeable doubling is confined to strips less than 0.05 in. wide, or 10 per cent of the total picture area, and (3) the standard 24-in. shutter has a shutter speed of only $1/150$ sec.

The lower print of Figure 118 shows the effect of the compensating screen on the bars of double exposure. The improvement is marked. It should be pointed out, however, that the shutter development, as such, was not carried to ultimate possibilities, and that further development work would lead to negatives showing less double exposure, followed by still better compensation on printing.



	TOTAL SCREEN MOTION x_p	x_s	TIME FROM POSITION (2) t
1	0	0	–
2	$\frac{d-w_s-w_p}{2}$	0	0
3	$\frac{d-w_s+w_p}{2}$	0	$\frac{w_p}{V_p}$
4	$d-\frac{w_s}{2}$	$\left[\frac{d-w_s}{2}\right]$	$\frac{d+w_p}{2V_p}$
5	$\frac{3d-w_s-w_p}{2}$	$d-w_s$	$\frac{d}{V_p}$
6	$\frac{3d-w_s+w_p}{2}$	$d-w_s$	$\frac{d+w_p}{V_p}$
7	$2d-w_s$	$d-w_s$	–

FIGURE 115. Shutter screen motion, Type 1.

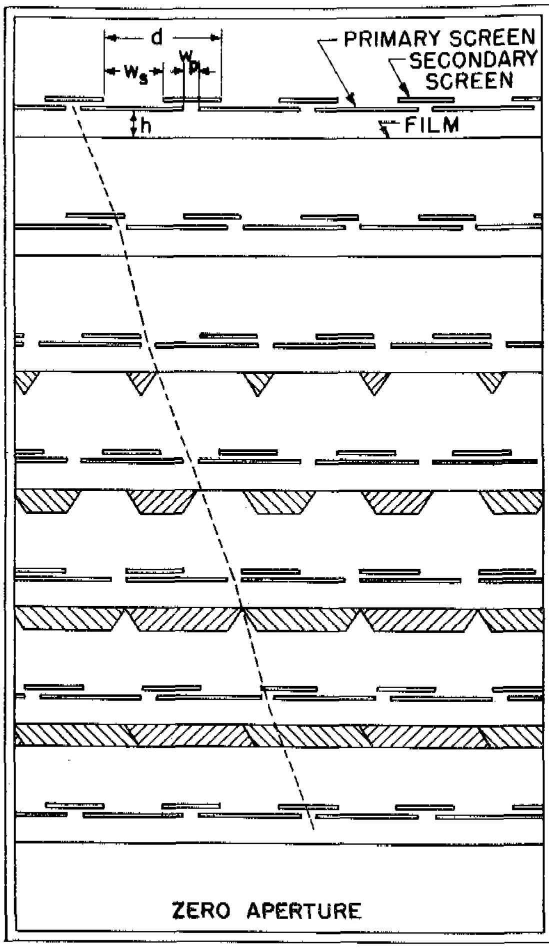
THE TECHNICOLOR MULTIPLE SLIT SHUTTER[30a]

Following the developments described above, work proceeded at the Technicolor Motion Picture Corporation on an improved version of

[redacted]

Type 1 described above. In the Technicolor form the primary screen containing narrow slots ($\frac{1}{16}$x9 in.) moves over the stationary secondary screen containing wide slots ($\frac{1}{4}$x9 in.) until the narrow slots are in the centers of the wide slots and therefore exposing. At this point the two screens move together for a distance of $\frac{1}{4}$ in., producing uniform exposure through case at a time when this blade is stationary. The primary screen merely determines the exposure time, and it stops after the secondary screen has stopped.

2. Overlap is theoretically reduced to a very small amount, which depends only upon the distance of the secondary screen from the film and on the angular aperture of the lens.



	TOTAL MOTION, x_p OF PRIMARY SCREEN — GENERAL CASE	IF $w_s = \frac{d}{2}$	TIME FROM POSITION 2
1	0	0	—
2	$\frac{(d-w_s-w_p)d}{2w_s}$	$\frac{d}{2}-w_p$	0
3	$\frac{(d-w_s+w_p)d}{2w_s}$	$\frac{d}{2}+w_p$	$\frac{w_p d}{V_p w_s}$
4	$\frac{d^2}{2w_s}$	d	$\frac{(w_s+w_p)d}{2V_p w_s}$
5	$\frac{(d+w_s-w_p)d}{2w_s}$	$\frac{3d}{2}-w_p$	$\frac{d}{V_p}$
6	$\frac{(d+w_s+w_p)d}{2w_s}$	$\frac{3d}{2}+w_p$	$\frac{(w_s+w_p)d}{V_p w_s}$
7	$\frac{d^2}{w_s}$	2d	—

MOTION OF SECONDARY SCREEN

$$x_s = x_p \frac{d-w_s}{2}$$

FIGURE 116. Shutter screen motion, Type 2.

the narrow slots. At the end of this run, the secondary screen stops, and the primary screen keeps moving until the exposure stops altogether.

The following points apply to the Technicolor version:

1. The edges of the secondary screen (wider slots) limit the width of the exposure in each

3. Streaks of unequal density are much more likely to occur with this design than with the original Langer shutter, due to difficulties in keeping the primary screen traveling at uniform velocity, especially since the secondary screen must be started and stopped during exposure of the $\frac{1}{2}$-in. strip. It is also essential that stresses due to acceleration shall not dis-

[redacted]

tort the primary screen if streaks are to be avoided.

4. Greater mechanical precision in the positioning of the secondary screen as well as avoidance of distortion of the edges of the slots is necessary, since accurate butting of the $\frac{1}{2}$-in. strip pictures is entirely dependent on the secondary screen.

Driving Mechanism. Four types were considered: (1) modified Geneva movement, discarded because of limited throw of driving bell crank,

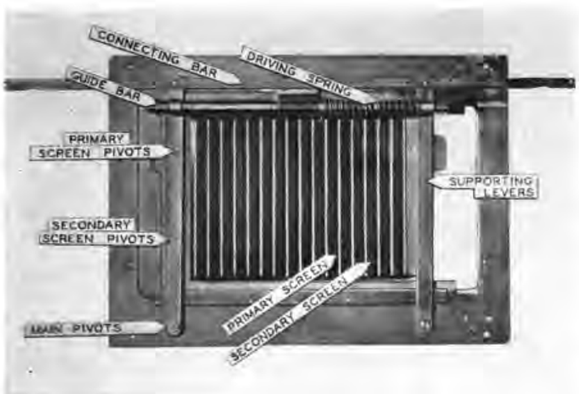


FIGURE 117. Test model of multiple slit shutter.

(2) oscillating cam mounted on the bell crank of the main drive, discarded because of hammer blows on the secondary screen, (3) a two-spring drive actually used, and (4) a pair of linear cams, one on either side of the secondary screen, used in the final version.

A standard 9x9 magazine was modified to incorporate the multiple slit shutter very near the film plane for the purpose of increasing the efficiency of the shutter action. The final shutter was positioned only $\frac{1}{8}$ in. from the film.

Preliminary experiments were made with small blades made of $\frac{1}{64}$ Duralumin, 8 in. long by 2 in. wide. The primary blade placed closer to the film was pierced with a slot opening, $\frac{1}{16}$x$\frac{1}{4}$ in. The secondary blade was pierced with a slot opening, $\frac{1}{4}$x$\frac{1}{4}$ in. Preliminary tests with this shutter were used to work out the proper balance between the two driving springs. Exposure times as short as $\frac{1}{1,500}$ sec were recorded.

Further tests were conducted on full 9-in. length blades, but with slots only $\frac{1}{16}$ in. wide by 1 in. long in groups of six, placed at the center and four corners of a 9x9 frame. The difficulties encountered in the testing of 8x2-in. blades again appeared. Over a period of two months approximately fifty tests were made on these blades to study the effects of shock and acceleration on the various parts. It was found that if Duralumin were used for the plates, it should be surrounded by a steel frame for strength and rigidity.

Following the tests on the double spring drive, a double linear cam drive was designed and constructed. Although sensitive to errors of construction, this system of driving the blades is positive in its action. The prototype system functioned very well, but the negatives were afflicted with shadow lines, both bright and dark. A series of tests indicated that there appeared to be no optimum overlap for the shutter action.

A complete shutter was made up making use of new cams, whose design was based on the experience of the previous tests, together with a sandwich type of blade design. In this form three screens were used. The first (primary) screen carried $\frac{1}{16}$-in. slots and governed the exposure. The third was rigidly fastened to the same frame and carried slots $\frac{1}{8}$ in. wide. The second screen moved on the first, and the first on the shutter frame. The advantages of this type of construction were (1) compactness, (2) reduction in friction between the first and second frames, (3) rigidity and less chance of distortion, and (4) frame under tension, not compression. The disadvantages were (1) complexity of design and assembly, (2) higher precision of frame parts, and (3) necessity of weakening the base plate of the standard magazine.

Summarizing the results of extensive tests made on the completed 9x9 sandwich shutter, we have the following data.

The advantages of the multiple slit shutter over the existing types of shutters have been attained to a great extent in regard to:

1. Shorter travel of blades—$1\frac{1}{16}$ in. instead of 9 in.

2. Higher exposure speed—$\frac{1}{700}$ sec observed, instead of $\frac{1}{300}$ as in the K-17 standard shutter.

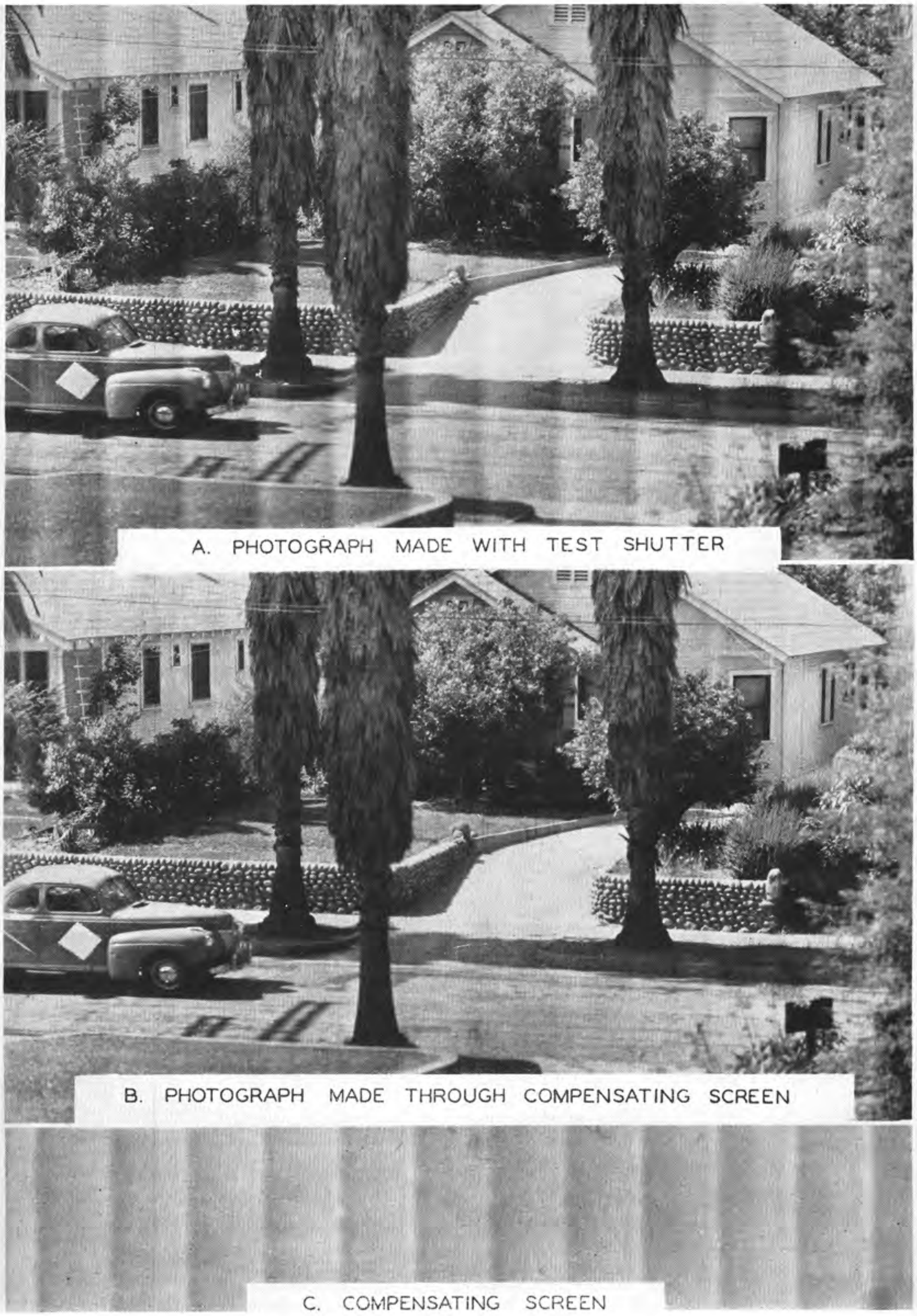


FIGURE 118. Photographs made with multiple slit shutter.

[redacted]

Speed up to $\frac{1}{1,000}$ sec could be achieved in a production model.

3. Closer approach to simultaneous exposure over the entire picture area.

4. Longer life. With proper design and materials a Langer-type multiple slit shutter could probably be made to operate for a long period of time with minimum maintenance.

The above advantages have been offset to a large extent by lack of uniformity in the picture area. This occurs in two or more places, and is produced by unrelated factors. The greatest nonuniformity is at the junction of the ½-in. strip pictures, and is caused mainly by the difference in the exposure gradient at the start and end of the ½-in. strip. This abutting of the pictures is a very critical matter, and considerable further experimentation would be necessary in order to improve this region to any noticeable extent. The second nonuniformity, which is not serious, is caused by the change in velocity of the $\frac{1}{16}$-in. slot in the primary screen. This trouble could no doubt be improved in a production model by further development of the driving system.

1.7.4 Miscellaneous Shutter Types

No other shutter types actually reached completion under NDRC, but some work was carried out on experimental models. Under Contract OEMsr-622[31] the Eastman Kodak Company considered several types of unorthodox between-the-lens shutter designs and made test models of a few. In this work a goal was set for a 3.5-in. aperture and 0.001-sec exposure time.

Bartol Model. Two model shutters made at the Bartol Research Foundation were turned over to Kodak for further development. In both models two sets of rotating disk-type blades with three blades in each set were used. The set of blades which actually determined the speed of exposure rotated at four times the angular rate of the second set and, consequently, could be timed to make approximately three and three-fourths revolutions before the openings in all of the blades coincided with the aperture.

The first model was driven by an electric motor, but was not further used, owing to a request to avoid use of electric power. The second model utilized compressed air at 250 psi. An analysis of pictures made with this model showed a total open time of between $\frac{1}{150}$ and $\frac{1}{200}$ sec, with an effective exposure time of $\frac{1}{300}$ sec. Instead of increasing the speed of this model, resort was made to explosive driving power by means of blank cartridges. These experiments were afflicted with breakdowns caused by the products of combustion of the explosions. No further work was carried out on this model.

Design work was carried out on a similar shutter driven by explosive force, with better distribution of the forces involved. Computations showed, however, that the design would lead to mechanical complications and excessive forces. Work on such shutters was stopped at this point.

Vane-Driven Shutter. In view of the difficulties with the above types, it was decided to investigate other sources of power. One device proposed was a single-bladed shutter powered by an external wind-actuated vane. This vane might be compared to a weathervane suddenly reversing its direction. Computations indicated, however, that the size of vane required for the short exposure time desired would be impractically large. It was estimated that a 6x6-in. vane at the end of a 1-ft arm would give an exposure time of only 0.01 sec, at a plane speed of 250 mph. No further work was carried on.

Continuously Operating Blades. This design consisted of a single pair of differentially geared blades rotating in opposite directions at slightly different speeds. The exposure was made when apertures in the two blades finally came into line across the aperture. To provide control of the interval between exposures and to allow rewinding of the film, an auxiliary shutter was to be so connected that it could be operated when desired, would stay open for one exposure only, and would then close until tripped again. Such a continuously operated shutter would avoid the heavy accelerations of the other types of shutters.

No actual shutter was constructed because of lack of need by the Services for fast, small shutters, and because of the impracticability

of large disk shutters. A simple model to show the principle was made up, with 3¾ in. aperture and 55 per cent efficiency.

Continuously Operating Focal Plane Shutter.[7] It was proposed under the Harvard contract to construct a magazine and focal plane type shutter in which the shutter passed over the film plane, over rollers around and back of the film rolls, and over rollers to the film plane again. Such a shutter would carry the usual focal plane type slit and pass very near to the film plane for high efficiency. Moreover, continuously operated, a rather high linear speed could be achieved without requiring unusual strain on the flexible curtain. It was thought that a slower between-the-lens shutter or capping curtain could govern the single exposures and open before the slit reached the emulsion and close after its passage. The longer the travel of the continuously operating curtain, the more time would be available for the slower shutter operation. No working model was constructed, owing to the end of World War II.

1.8 MISCELLANEOUS EQUIPMENT FOR AERIAL PHOTOGRAPHY

1.8.1 A Method for Checking the Focus of Aerial Cameras (Technicolor)[32]

Under Projects AC-29 and AC-88, in studies of factors that limit resolution of aerial photographs, it was decided to produce a device for testing the focusing of aerial cameras. Such a device serves the following purposes:

1. To determine for any lens, from a series of photographs taken at equally spaced focal settings, the accuracy with which the focus must be established in order to avoid any significant loss in resolution.
2. To determine the accuracy of focal setting of service cameras.
3. To determine the accuracy with which the optical axis of the lens is set perpendicular to the film plane.
4. To set the focus of cameras at the best setting for test flights.

Considerations of various possible methods led to the selection of a simple 35-mm camera attachment to the camera body. The special camera back required carried five ports, to any of which could be attached a Kodak 35-mm camera. The most important feature of the device was the micrometer adjustment whereby it was possible to obtain exposures by chosen increments at any focusing position inside or outside of focus. Figure 119 shows a view of the final device. The device was used extensively on the Mount Wilson optical bench for lens tests.

1.8.2 A Collimator for Testing Focal Setting (Mount Wilson)[19]

A portable collimator was constructed at Mount Wilson for the purpose of field tests of Army aerial lenses. The collimator consisted of a 3.5-in. doublet lens of 30 in. focal length

FIGURE 119. Focus testing device.

mounted in a steel tube. A lamp house at the opposite end made use of a condensing lens, a diffusing screen, a two-filament headlight bulb, and a pair of inclined reticles. The reticles consisted of photographs on glass plates of ink drawings of eleven pairs of fine lines intersecting at small angles. These reticles were placed at the focus of the collimator at right angles to one another and inclined 16 degrees to the optical axis. Successive fine patterns were separated in focal distance by 0.015 in., giving a total focusing range of about 0.15 in. The collimator was used in testing the focus and off-

[redacted]

axis resolution of a standard 24-in. $f/6$ aerial lens.

1.8.3 Exposure Meter (University of Michigan)[33]

In order to obtain satisfactory aerial pictures with standard lenses, usually troubled by vignetting, it is necessary to be within one or two stops of the proper exposure to fit the lighting conditions. Otherwise, the pictures will either be heavy and of muddy resolution, or else so light that the corners will fail to print out properly. Indeed, the rule-of-thumb methods used during World War II stressed a slight over-exposure in order to prevent total loss of under-exposed pictures. On the other hand, the exposure range encountered in flying weather under military conditions is very large.

In order to provide some means of determining the exposure level and to fill in the inevitable lapse of time until suitable photoelectric automatic shutters or iris diaphragms might be developed, the University of Michigan was requested under Contract OEMsr-1245 to design and make a prototype of a visual meter.

Figure 120 shows a schematic view of the optical arrangement. The photometer cube contains a small annulus of comparison light superposed on the general field in focus of ground light from the viewfinder. The viewfinder lens and ground glass are shown in the proper position for use in the air. Figure 121 shows one of the two prototypes built under the contract and its approximate size.

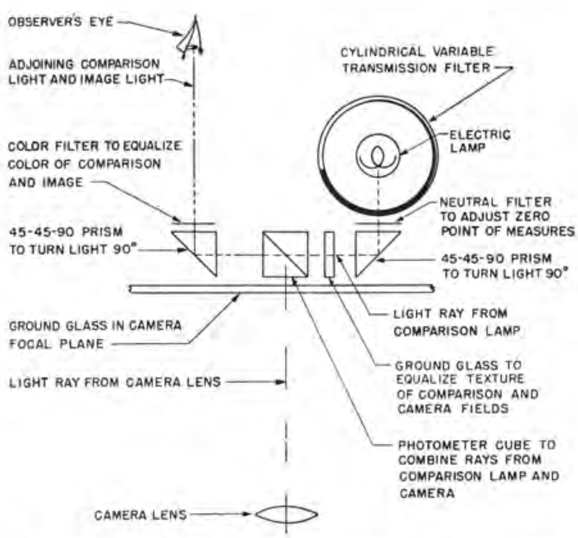


FIGURE 120. Schematic drawing of exposure meter and camera.

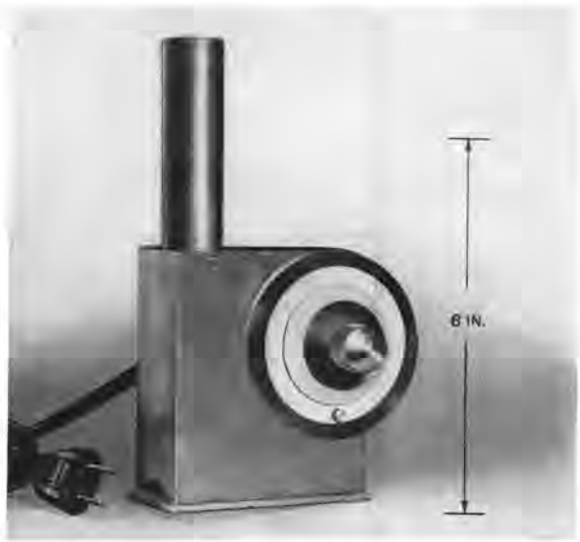


FIGURE 121. Exposure meter, Model 1b, assembly view.

1.8.4 Film-Flatness Tester (Harvard)[34]

An examination of numerous prints of aerial photographs shows the existence of random spots of poor focus, particularly evident on 9x18 photographs. Under Contract OEMsr-474, Harvard undertook to devise and construct a device for the purpose of measuring departures from flatness of film under service conditions.

Figure 122 shows a sketch of the final apparatus constructed at Harvard. In essence it was planned to use sixteen separate Hartmann tests at uniformly spaced intervals over the area of a 9x9 picture. Plans were under way for construction of a similar device for the A-7 and A-8 magazines which are designed for 9x18 photographs.

No final analysis was made at Harvard, owing to the termination of the contract. The report suggests that the equipment is not quite

complete for a service test and would profit by an automatic means for changing the film. It was planned to set the equipment up experimentally in a medium-sized cold and low-pressure chamber and to operate a succession of films under conditions likely to obtain in the air.

For ease of use, the light source was to be a small sodium aperture at a distance of 8 ft along the central vertical of the picture. Each of the sixteen identical lens elements was covered by an opaque brass disk perforated in a Hartmann pattern. The twelve holes of the

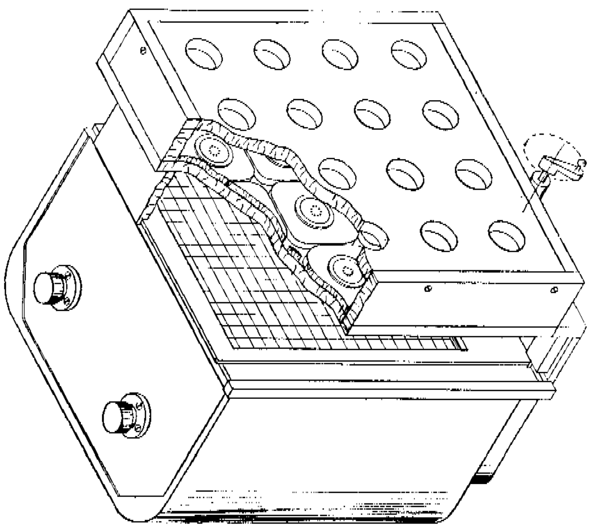


FIGURE 122. Schematic view of film-flatness tester.

pattern were round and of a diameter found by experimental testing to be optimum for the exposure time planned. The rays defined by each Hartmann hole on a single circle of proper diameter pass through a common focus about $\frac{1}{8}$ in. in front of the film plane. The Hartmann pattern is therefore out of focus and photographs as a miniature pattern of the original perforated plate. All of the lenses are adjusted separately to yield a common focus on a plane for a light source at the distance specified. The oblique projection causes an elliptical spread of the small Hartmann spots, but the important consideration is that the defining focal plane carries with it a specific diameter constant throughout the photographic run, and that variations from frame to frame can readily be detected.

If film is run through the device at intervals of 5 sec or so, the Hartmann patterns photographed will have a maximum diameter defined by perfect positioning of the film. If the film bulges forward, the Hartmann pattern will contract. By very elementary geometry, it is possible to determine from the contraction how much the film has bulged. Indeed, the method is so accurate in terms of thousandths of an inch, that it is necessary only to measure the separation of two spots across a diameter lying perpendicular to a line in the film plane running from the center of the picture. For economy of reduction one can use a projection system and a direct reading scale showing departure from flatness.

The Harvard report mentions that a number of magazines used in the Services were received and examined. Only two out of six were in first-class working order. Three of the other four had vacuum leaks to the extent that the film could not have been held flat. Another had been damaged mechanically. The report also mentions that on photographs obtained from time to time, quite far out of focus, there were spots here and there of great sharpness, indicating that the film had bulged forward through the focal surface. It is suggested that, based on this experience, a simple test could be applied by any organization interested in flight testing its magazines. One would preferably use a hard focus lens at maximum aperture, and work approximately 1 mm out of focus. Spots of sharp focus are more easily found on soft photographs than are soft spots on sharp photographs.

Discussion

The film-flatness tester should be completed and used for extensive tests of a previously renovated A-5 magazine. Similar tests should ultimately be conducted for A-7 and A-8 magazines which are much more likely to have vacuum troubles.

It would be very informative to examine the results obtained with a half-dozen magazines reclaimed from the Services in order to ascertain what difficulties were most usually encountered, and to what extent magazine troubles limit the quality of Service photographs.

[redacted]

1.8.5 Cold Chamber for Camera Tests (Harvard)[35]

Under Contract OEMsr-474, Harvard constructed in 1943 an elementary type of cold chamber for conducting tests on the thermal properties of the 40-in. telephoto and the fluorite apochromatic lenses. Relative to the investment, the cold chamber provided many useful results in guiding later work.

In 1945, work was begun at Harvard on a much more analytical form of cold chamber, which was also to include pressure testing. The earlier cold chamber work made use of autocollimation and a quartz flat. The later proposal was to use only a single passage of light as a better guide to image characteristics of lenses under extremes of cold and apparent altitude and to effects of thermal and pressure gradients.

The cold and pressure chamber was to consist of a pipe 26 in. in diameter and nearly 4 ft high. A smaller pipe was to be welded to a base plate at the bottom of the larger pipe and was to extend 30 in. more into the basement below. This smaller pipe was to contain cells at the upper and lower ends for holding two 10-in. diameter optical windows of BSC-2 glass, nearly 2 in. thick.

The light path planned was to start at the focal plane of the lens under test within the chamber. A resolution target or any other form of target would be fastened securely in the focal plane of the camera under test. The light would then pass downward through the rear element and become more or less collimated by the camera lens. The emerging nearly parallel beam would then pass through the first window placed at the level of the first floor and base ring of the vacuum chamber. The space between the two windows, nearly 30 in. in extent, was to have been evacuated in order that heat waves in the transition region between extreme cold and the room warmth would have no effect whatsoever on the optical path, and in order that condensation be eliminated. The light would then pass through the 30-in. vacuum, through the second window into the basement air, down to a parabolic mirror below the basement floor, and then to an observing microscope by way of a very small diagonal mirror cemented to the lower face of the lower window.

Irrespective of the design details, it is apparent that such a cold and pressure chamber would afford the greatest comfort to the observer and would at the same time simulate conditions in the plane in every respect except vibration. The vertical position of the camera is desirable. Changes of focus are measured by the observing microscope under a longitudinal magnification varying as the ratio of the squares of the focal lengths of collimator and camera lens.

The cooling effect of the apparatus on the room will produce a slow shift in zero point during a run intended to measure change of focus of the lens within the cold chamber. For establishment of a zero it is expedient to use a Gaussian arrangement in the observing microscope which sends a beam of light through the objective from its own focal plane, to the collimating paraboloid, up to the lower face of the first window, and back again to the observer's eye.

The windows will act as hot radiators to the cold chamber, permitting much heat to enter by direct radiation. It would be nearly ideal to use a thin layer of gold on the lower face of the lower window. The gold film will reflect practically all the heat rays but will transmit very well in the visual. Such a film could have a thickness sufficient to return the reference beam of parallel light to the measuring microscope, enhanced relative to reflections from the other windows.

It is recommended that such a cold and pressure chamber be carefully designed and constructed for use in further testing in the laboratory. All wartime results point to the importance of knowing thermal gradients as well as temperature. Consequently, it would be of the greatest importance to include electric refrigeration and heating controls for the establishment of any arbitrary cooling curve desired. The effect of heating on position of focus, followed by rapid cooling, should be studied in an attempt to simulate thermal and military conditions in all parts of the world. Some thought should be given to installation of circulated air in an attempt to imitate the slip

stream and its cooling action which was shown in the Harvard test flights to cause significant changes in the position of focus of large lenses.

1.8.6 Aerial Camera Stabilizer

A project was initiated in Division 7, NDRC, for the purpose of developing a gyroscopic mechanism for stabilizing large aerial cameras. Tests of the device finally constructed were confined to a wooden mockup of an aerial camera and conducted on a rocking platform.

Whereas the usual type of stabilizer in effect couples the camera to the plane through the servo mechanism, which is generally too slow to respond to the higher frequencies and transmits them, the proposed type of design involves a pneumatic piston-operated actuator working at low pneumatic pressures. It was believed that such a system would permit the application of restoring forces through the actuator. The system is therefore analogous to one employing weak restoring springs that in themselves would be unable to transmit high-frequency vibrations to the camera.

For a reference system, it was decided to make use of an angular rate gyro with pneumatic pick-off and flexure gimbal bearings already developed for other purposes. The reader is referred to the NDRC Division 7 report[36] for engineering details of the coupling. In principle, the gyro is counterbalanced continuously by pneumatic forces in pick-off cups, which are in turn translated into corresponding differential pressures. A pressure amplifier is included which converts the differential pressure into twentyfold amplified actual pressure in a cylinder fastened to the air frame. A piston in this cylinder is attached to the camera. Any pressure in the cylinder, proportional to the original differential pressure, moves the piston and therefore the camera with respect to the air frame for maintenance of the gyro-controlled vertical.

Test results showed that for a 1.5-sec period, and for an amplitude of approximately 10 degrees, the angular departure of the camera from a fixed position was about one-fifth of 1 angular mil. When the camera was forced off the true vertical and allowed to return, the time elapsed for it to come within one-third of its original tilt was 20 sec. In the absence of platform rocking, the camera was observed to come within a 6-mil hysteresis band of the true vertical. Any rocking of the platform, however, caused the camera to come within a fraction of 1 angular mil from the true vertical, and more nearly simulated conditions in the plane.

For application to an actual aerial camera mount, it would be necessary to add a second axis of stabilization not present in the working model in order for the camera to find a true vertical. Moreover, it is likely that the tests to date have not fully simulated aircraft conditions with respect to range of frequencies and amplitudes, and that time lag in cross product with natural frequencies and sensitivity of the gyro control may actually introduce small scale motions likely to upset the quality of the aerial photograph. Any stabilizing device working on detection of rate must be watched for this "three walnut game" to ascertain that the quality of the photograph is maintained. It is also necessary to incorporate a sweep mechanism and preferably an antivibration mount in the stabilization device.

1.9 RECOMMENDATIONS BY NDRC

1.9.1 Lenses

1. The development of high-resolution lenses of long focal length should be continued, emphasizing high resolution scores based on area, wide angular coverage, preservation of microscopic contrast, maximum speed, and minimum vignetting.

2. The following lenses should be given special attention:
   a. 36-in., $f/8$, 9x18-in. anastigmat, to replace the 36-in., $f/8$, 9x18-in. telephoto, with better resolution over the entire area.
   b. 60-in., $f/5$, 9x18-in. telephoto, with sealed construction to permit evacuation.
   c. 72-in., $f/8$, 9x36-in. anastigmat, for the combination of maximum resolution, focal length, and angular coverage.

d. 100-in., $f/10$, 9x18 in. This lens should be equipped with an antioscillation mount and should then be fully tested.

3. Special lenses for extremely wide angular coverage should be developed. The same result may be achieved by using twin camera mounts or by using an optical device to aim the camera successively in two or more directions. The Harvard-NDRC 6-in., $f/2.85$, 120-degree lens should be mounted and tested. If the value of this lens is demonstrated in a spherical shell camera, an automatic mechanism for changing shells should be developed. It will, however, probably be entirely practical to change shells by hand.

4. All long-focus lenses should be hermetically sealed and thermostated so that they may give full performance. Automatic focusing is not necessary if the lens is provided with manual adjustment for approximate altitude.

5. New optical materials, particularly fluorite, barium fluoride, spinel, and some of the alkali halides should be developed further and applied to the design of long-focus lenses for high resolution, particularly for color photography. The 48-in., $f/8$ glass-fluorite lens should be completed.

6. Lenses and cameras for night photography should be developed further, particularly the Harvard-NDRC 8-in., $f/1.3$ Schmidt camera for 35-mm film, to be used with Edgerton flashes, and the University of Rochester-NDRC 6-in., $f/1.0$ lens with curved field. Methods should be investigated for reducing scattered light when using Edgerton flashes, perhaps by employing sources rich in red light or by using polarized light.

1.9.2 Shutters

1. Focal plane shutters, with speeds up to $\frac{1}{1,500}$ sec, with high efficiency and smoothness of operation, and with minimum vibration, should be developed. High speed offers the only hope for improving resolution markedly before better mounts are available. Higher speed can probably be achieved better with focal plane shutters than with between-the-lens shutters. It is essential that the shutter blind be located extremely close to the film, as the result of special design of shutter and magazine. It may not be possible to use standard magazines.

2. A continuously operating blind for a focal plane shutter should be developed if possible to reduce vibration and to equalize exposure over the entire film.

3. Further studies of the Langer shutter should be made to determine whether this type of shutter has useful applications. If so, the direct linkage of the blinds, suggested at Mount Wilson, should be investigated.

1.9.3 Mounts

1. Changes in the Eastman-NDRC mount should be made if indicated by carefully planned tests which should be conducted at the earliest possible moment.

2. Other types of high-frequency filtering mounts should be investigated and developed if found to be promising.

3. Development should be made of a mount for several cameras on a single rigid frame, with the maximum attainable moment of inertia and the longest possible period, supported at the center of gravity of the system, with damping and restoring force, and with a sweep mechanism. Such a unit would be entirely practical in a bomber and offers one of the most promising outlooks for reducing angular motion.

4. The Harvard-NDRC center-of-gravity mount should be studied and developed further, with provision for releasing the camera at a moment when the angular rate is low, or else with provision of restoring force and damping. Experiments should be tried with a weak restoring force and no damping, with provision for caging the camera when making turns.

5. Studies of angular vibration data of the fuselage in various types of aircraft should be made to determine the best combination of natural period, restoring force, and damping, in order to give the minimum angular velocity to the camera.

[redacted]

1.9.4 Specially Engineered Lens-Camera Systems

1. A 36-in. focus camera, with 9x18 in. coverage should be developed using the best available design for the lens and shutter, and with a mechanical design which emphasizes lightness and dependability. This camera would be very useful in single-seater reconnaissance planes, including jet planes.

2. As soon as flight test data have led to a definite understanding of the factors which limit resolution in aerial photography, a project should be initiated to combine in one complete practical camera system all of the knowledge and technological skill available, based at the start on a 12-in. focal length camera, with a goal of 40 lines per mm resolution. Photographs as sharp as this would be equivalent to present photographs taken with cameras having more than twice the focal length. Experience gained should next be applied to longer focal lengths.

[redacted]

Chapter 2

RESOLUTION IN AERIAL PHOTOGRAPHY

By *Duncan Macdonald, Theodore Dunham, Jr.,* and *James G. Baker*[a]

2.1 INTRODUCTION (HISTORICAL)

The importance of aerial photographic reconnaissance has become generally acknowledged and assigned a high priority among the techniques of modern warfare. Aerial photography provides a large part of the information about enemy territory, about the identification and dispersion of men and materials, and about the damages inflicted by offensive action which serves as the basis for further military operations.

The usefulness of an aerial photograph depends to a large extent on the detail which it records. In general the ability to distinguish and identify objects on the ground increases very rapidly with increasing quality of the photograph, so that even a moderate gain in quality yields valuable additional information for the interpreter. The value of high-resolution aerial photographs in peacetime is equally great for precision mapping, and for agricultural and geological surveys, in which the maximum attainable detail can be used to great advantage.

As the importance of high-quality aerial photographs was well recognized, consequent provision was made in the early stages of World War II to support investigations directed toward improvement of resolution in aerial photography. In October 1941, the Army Air Forces requested Section D-3 (Instruments) of NDRC to undertake Project AC-29, covering a variety of investigations directed toward this end. In February 1943, AC-29 was expanded to include the development of certain specific lenses. Since then the scope of AC-29 was further increased to include the development of a 40-in. $f/5$ lens and of a wide-field lens that had been started at Harvard in April 1941, under a direct Army contract. In March 1942, NDRC asked the Eastman Kodak Company to investigate the entire subject and to design a lens having the highest possible resolution, even if it should be necessary to limit the useful field severely. The workers at Eastman became convinced, however, that more would be gained from reducing vibration than from increasing inherent lens resolution, and accordingly, concentrated their first efforts on developing an improved antivibration mount. Somewhat later, Eastman did develop two lenses of very high quality, but these developments were not carried out under NDRC.

The Mount Wilson Observatory was asked by NDRC to develop methods for producing Schmidt correcting plates of high accuracy which would be suitable for production in case it were found desirable to employ these cameras in aerial photography. In 1942, the Observatory undertook the development of a 30-in. 2-mirror Schmidt camera[1] to evaluate the usefulness of this type of camera for precision photography from high altitudes and to determine whether the various mechanical difficulties connected with the design could be overcome. The experience at Mount Wilson shows that for large Schmidt cameras these difficulties are so considerable that lens cameras are much to be preferred if they can be designed to give comparable resolution. At the beginning of World War II it was uncertain whether long-focus lenses could compete with Schmidt cameras in giving precision resolution. But by 1944 it had been clearly demonstrated that lenses having resolution at least comparable with that of photographic emulsions over very considerable fields could be designed and, what is equally important, that they could be made under production conditions without sacrificing quality. This demonstration of the capabilities of lenses reduced the need for pushing the development of long-focus Schmidt cameras for daytime reconnaissance.

The development of special lenses at Harvard

[a] The material in this chapter has been compiled by Dr. Duncan Macdonald (Boston University), with the collaboration of Dr. Theodore Dunham, Jr. (Chief, Section 16.1, NDRC), and Dr. James G. Baker (Harvard College Observatory).

University was transferred to Section D-3 of NDRC in September 1942. This project was assigned to Section 16.1 of NDRC in December 1942. During the next three years the scope and the available facilities at Harvard were steadily increased, until the ending of World War II made it necessary to terminate the NDRC program. Several long-focus lenses of unusually high performance were developed.[2,3,4,5] These included lenses containing single fluorite elements, which are nearly free from color aberration, and lenses with very wide angular coverage. Important improvements were made in methods for mounting lens elements with the required precision and for protecting the optical systems against invasion by moisture and fungus, which often has a disastrous effect on otherwise excellent lenses, particularly in the tropics.

In addition to this development work, Project AC-88 was established in May 1944 to cover the need for a systematic study of the factors that limit resolution in aerial photography, also offering provision for laboratory and flight testing of equipment developed under Project AC-29. Under Project AC-88 resolving-power targets were constructed at Wright Field, Dayton, Ohio, by the Massachusetts Institute of Technology [MIT] in cooperation with the Photographic Laboratory of Wright Field.[6]

Flight tests using standard AAF equipment were conducted in the summer of 1944 at Wright Field over the resolving-power targets. These tests were conducted and assessed as part of a cooperative program by Mount Wilson, MIT, and the Photographic Laboratory. This program consisted of seven flights with a standard 24-in. camera in the standard mount of an F-5E airplane. In addition to this program, fifteen other missions were flown, some at night over flashing lights, some in the daytime over the resolving-power targets, and others over sun-illuminated spheres. These missions were designated as vibration studies and the data interpreted in terms of the quality of antivibration performance of the camera mounts. This latter program extended into the spring of 1945.

Early in 1945 it became obvious that progress in evaluating the factors which limit resolution could only be made rapidly enough to lead to improvements in equipment which might yet have an effect on the war if an intensive flight testing program were undertaken in close conjunction with one of the NDRC laboratories, with a special airplane and crew assigned for the purpose. At that time, an expansion of the staff and facilities of the Harvard laboratory was being considered in order to expedite completion of new lenses which were urgently needed. Section 16.1 of NDRC regarded a knowledge of the factors limiting resolution as essential for realizing the potential advantages of precision long-focus lenses, but recommended that the laboratory and shop facilities at Harvard should be expanded only if an airplane were made continuously available at Bedford for flight tests. The Army Air Forces supplied a B-17 airplane late in June 1945, and this airplane or another of the same type was available without interruption through November 1945.

An extensive program was planned at Harvard to investigate all factors likely to affect the resolution of photographs. The termination of World War II a few weeks after the program was initiated prevented carrying out more than a small part of this program. After V-J Day the principal aim was changed from evaluation of limiting factors to that of achieving best possible resolution with available equipment. In spite of the sudden interruption which the project necessarily suffered, many extremely effective methods were developed and a large amount of very significant data was obtained on the fifty-five flights flown out of Bedford. It has not been possible to reduce and discuss more than a part of this data in the OSRD reports. However, the continued reduction of this data and the completion of the flight program are now being undertaken under the auspices of the Boston University Optical Research Laboratory and the Wright Field Photographic Laboratory.

2.2 STATEMENT OF THE PROBLEM

The resolution obtained on an aerial photograph is the result of the combined effects of

a number of factors. An upper limit of aerial resolution is determined by the performance of the lens in the laboratory, or more exactly, lens plus film laboratory resolution. When in the air, the peak resolution of a camera-film combination (laboratory performance) may be likened to a position of unstable equilibrium where the influence of ground speed, vibration, aircraft rotatory motions, shutter performance, haze, focal setting, temperature, air turbulence, the presence of a photographic window, and other factors add together to pull resolution down to a lower, more stable level. In addition, exposure level and photographic processing techniques have considerable influence on the observable detail in the finished negative or print. Here, then, are really two closely related problems: (a) a comparison of laboratory and in-the-air performance of both standard AAF and NDRC equipment, and (b) an evaluation of the individual factors that add together to cause the gap between laboratory and in-the-air performance, with the aim to minimize those factors found to be most detrimental. In the following sections there will be presented a description of the methods and a discussion of the results of the studies by Section 16.1 of NDRC related to resolution in aerial photography.

2.3 RESOLVING-POWER TARGETS

In a program directed at the evaluation of in-the-air performance of photographic equipment, it is of course necessary to provide resolving-power targets on the ground to enable a quantitative scoring of performance of this equipment. Four sets of targets were constructed for use in the resolution program.

In 1942 the Mount Wilson Observatory constructed four circular painted canvas patterns, each approximately 30 ft in diameter and consisting of 32 sectors alternately light and dark.[7] Each pattern was of different contrast. Although preliminary tests of equipment were conducted over these targets, rapid accumulation of dirt on the canvas indicated the need for an improved type of target construction.

Four parallel-line resolution patterns painted on masonite sheets were then constructed by Mount Wilson, each pattern of different contrast, consisting of six pairs of 4x8 ft panels hinged together. The unit structure selected for this pattern was later adopted as an unofficial standard for all other resolution targets constructed by Section 16.1, and is described in the following text. These masonite patterns were damaged by wind while in use at Blythe, California, in connection with tests of the 40-in. $f/5$ telephoto lens developed at Harvard.

It became apparent that for a long-range testing program, permanent resolution targets were required, targets that would not demand constant attention and which would retain their photometric characteristics.

With the establishment of Project AC-88, the first set of these permanent targets was constructed at Wright Field. It was agreed, after considering several types of installation, that patterns painted on concrete slabs would prove to be the most satisfactory type. The Army Air Forces then installed five concrete slabs along the E-W runway at Wright Field, and MIT sponsored the painting of the thirteen parallel line resolution patterns on these slabs.[6a]

This project required the development of optically neutral paints with a high degree of color permanence, good weathering qualities, and strong adherence to concrete. This was done at MIT by first modifying a white (titanium oxide) highway paint to conform with the mechanical requirements of the problem and, second, by determining percentage weight composition of this paint and two paints of similar composition but containing carbon and ferrous oxide pigments to give optical neutrality at any desired reflectance level.

The choice as to types of resolution pattern for the targets soon was limited to two—radial or parallel line. In the evaluation of a photograph in terms of resolution alone, these designs seem to offer as simple and as complete a result as possible. The radial pattern possesses the obvious advantages of giving resolution at all azimuths and avoiding discrete steps. On the other hand, the method of assessing parallel-line patterns can be made simple and the personal factor minimized. Moreover, in a parallel-line pattern, the ratio of line length to line

width, and its consequent effect on resolution, is constant. These advantages, coupled with the fact that parallel-line patterns were in general use, led to the adoption of this type of pattern. The disadvantage of discrete steps was overcome in part by the adoption of a small step factor ($\sqrt[3]{2} = 1.26$). To determine resolution both parallel to and perpendicular to the line of flight, two sets of lines were provided, one in the direction of the flight course, the other normal to this direction. The range of line widths (width of a single line) was from 1 to 30 in., covered in sixteen steps.

The length of each line was five times its width; the space between lines was equal to the line width. Resolving power is increased by increasing the ratio of line length to line width. At a line length to width ratio of 5/1, resolution approaches that value obtained for infinitely long lines while the overall dimensions of the target do not become too great. It is felt that resolving power as measured by such a pattern corresponds closely to the resolution of detail in aerial photographs.

It was found that three lines separated by two spaces was the ideal unit. Each unit therefore forms a square. If but two lines are used, spurious resolution may be assigned as true resolution. Also, from the point of view of the film observer, a criterion of resolution can be established for the three-line pattern that is more nearly independent of the personal equation. The criterion adopted was that a unit to be resolved must be seen as three lines separated by two spaces of uniform density regardless of the degree of contrast between lines and spaces. Thus the observers looked for two spaces rather than three lines. The use of more than three lines is unnecessary and would result in less correlation between observers, due to the difficulty that the human eye encounters in focusing on each of several uniformly spaced steps. The resolving power attained on a film was then defined as the reciprocal of the separation (lines per mm) on the film of the centers of the smallest bright lines of the pattern that were acceptable under the criterion set up to define a resolved unit. Resolving power in the line of flight was defined by the pattern lines normal to this direction.

The choice of pattern reflectivities was based on the fact that the landscape has an average reflectivity of the order of 16 per cent. This figure was then taken as an approximate geometric mean of the line-background pattern reflectivities. Two patterns were located on each of the five targets at Wright Field, one pattern of high contrast, the other of low contrast. In one target, three additional patterns were painted, one of the maximum attainable contrast with the construction method used, the other two of low contrast with one of high reflectivities and the other of low reflectivities. Unusual weathering conditions, due primarily to assorted dusts of various construction jobs, changed the target reflectivities from time to time. The proposed and initial reflectivities, and the change of reflectivities are shown in Table 1.

TABLE 1. Pattern reflectivities.

Pattern	Reflectivities in per cent: Proposed	Initial 7/22/44	8/10/44	9/2/44	11/6/44
High contrast					
Line	50	46.5	40.9	43.9	32.1
Background	5	3.0	3.6	6.1	6.0
Low contrast					
Line	24	25.0	20.5	27.9	22.6
Background	12	11.5	10.5	16.5	12.9
Maximum contrast					
Line	80	80.5	70.4	60.3	47.5
Background	5	3.0	3.6	6.1	6.0
Low contrast of high reflectivities					
Line	80	80.5	70.4	60.3	47.5
Background	40	39.0	34.1	35.3	27.9
Low contrast of low reflectivities					
Line	10	11.5	10.5	16.5	12.9
Background	5	3.0	3.6	6.1	6.0

In addition, three photometric areas each 40 ft square were located on the largest target. These areas were of proposed reflectivities—50, 16, and 6. A small area of each target (16x40 ft) was devoted to a 14-ft diameter, 64-sector radial pattern, a set of solid color circles, and several crosses. This area was to be devoted to use in studies of aircraft motions.

These targets, and an additional high-contrast parallel-line pattern and 40-ft diameter, 32-sector radial circle painted on one of the runways as a preliminary test of the painting

[redacted]

method, were employed throughout the summer of 1944 on the NDRC flight testing program.

When the aerial photographic testing program was consolidated at Harvard in the spring of 1945, another set of targets was constructed at the Orange, Massachusetts airport.[8] The airport has three little used 5,000-ft asphalt runways. Arrangements were made for use of one of these (the NE-SW) runways, and four resolution targets were then painted on this runway.

On the basis of experience gained through use of the Wright Field targets, and particularly from the British, a smaller step factor $\sqrt[6]{2}$ was employed in the parallel-line pattern. This eliminated the necessity for observers to interpolate between units in determining limiting resolution. The range of line widths on the Orange targets was from 2 ft to $1\frac{5}{16}$ in. The unit structure, which had proved itself to be most satisfactory, was identical with that of the Wright Field patterns.

It had been found that local defects in the emulsion often affect the selection of the last resolved unit when working at a high level of resolution. To eliminate this spurious loss of resolution, the eight smallest units were duplicated on these targets.

The plans for the target layout at Orange called for a single standard resolution pattern at each target. Because of this feature the choice of contrast and reflectivities was important. The analysis of the Wright Field tests had employed only the readings from the high-contrast target images. On the other hand, British and Canadian researches were mostly done on low-contrast targets. It is true that aerial reconnaissance, as used in military operations, deals for the most part with low-contrast objects, and a low-contrast target would therefore be most representative of actual conditions encountered in the field. The British point out that higher resolutions assigned with use of high-contrast patterns are not true representations of resolution of detail in the average military photograph.

On the other hand, any factor that enters to limit resolution will lower a high resolution number more than it will lower a low resolution number. It is desirable, then, in a study of factors that limit resolution to work at high levels of resolution where the numbers are more sensitive to change. This implies use of a high-contrast target for such studies.

The British have also pointed out that development of equipment may be carried farther than is practical through use of high-contrast studies; the argument being that equipment that will improve high-contrast resolution will not necessarily improve the low-contrast resolution encountered in reconnaissance. This may be true, but given ideal atmospheric conditions on any day, equipment tuned to give maximum resolution at high contrast will outscore equipment that has been tuned to give maximum resolution at low contrast. Also, it is true that low contrast and the effects of varying contrasts can be studied better under laboratory conditions where control factors are more easily imposed.

Because the measurement of resolution becomes less critical at lower contrasts, and because emulsion properties themselves, particularly graininess, are predominant factors in low-contrast resolution, it was felt that the standard pattern for the investigations should be of such contrast as to yield high resolution numbers. A 4/1 reflectivity ratio was proposed. The reflectivities of the finished patterns were 7.5 per cent for the background and 46 per cent for the lines.

In addition to this standard pattern, each target contained a small, high-contrast pattern (line reflectivity 88 per cent, background 7.5 per cent). Three of the targets possessed 40-ft diameter, 64-sector radial patterns and the fourth target an 80-ft diameter, 128-sector radial pattern. This latter target also contained five 40-ft square photometric areas of reflectivities 88, 46, 30, 10, and 4.0 per cent and three other resolution patterns of the same dimensions on the standard pattern. These three patterns were:

1. A reverse standard pattern, dark lines of 7.5 per cent reflectivity on a light background of 46 per cent reflectivity, used to investigate the effect of scattered background illumination.

2. A low-contrast pattern of low-exposure level, line reflectivity 30 per cent, background reflectivity 7.5 per cent.

3. A low-contrast pattern of high-exposure level, line reflectivity 88 per cent, background reflectivity 43 per cent.

These latter two patterns were designed for studies involving contrast and exposure level. This target also contained two other small patterns devoted to special tests. One pattern consisted of a series of dark lines on a white background, all lines of the same length but of widths varying by a factor of $\sqrt{2}$. This pattern was used for measuring loss of contrast with decreasing line width. The other pattern consisted of nine sets of solid dark circles. In each set the diameters varied by a factor of $\sqrt{2}$. Three sets were painted on each of three different backgrounds, each set in a given background of a different reflectivity. This pattern was to be used to study effects of scattered light and contrast in limiting the size of detail observed. Two of the other runway targets also contained three 40 ft square photometric areas.

A small masonite parallel-line target was installed alongside the runway at the Orange Airport. This contained colored targets, yellow on gray, gray on yellow, red on gray, and gray on red. It was used in studies of resolution of colored objects and to compare the relative color corrections of various lenses.

Figure 1 is an enlargement of the large target at Orange showing the design of the standard pattern, the target layout, and the special patterns. This photograph was taken from 10,000 ft with the 40-in. $f/5$ Harvard-NDRC lens.

The choice of the standard resolution pattern has proven to be satisfactory in all respects. In addition, there was no measurable change of reflectivity of the Orange targets during the time that they were employed. Recent observation has indicated that the paints have endured a New England winter without noticeable deterioration or change in reflectivity.

2.4 PERFORMANCE OF STANDARD EQUIPMENT

It is natural to inquire what level of resolution is achieved at the present time under representative operating conditions with standard equipment and regular personnel. It is extremely difficult to obtain anything approaching quantitative information on this point because it has obviously been impractical to install resolution targets in regions where military operations were being conducted. It would, however, be entirely practical to install test targets near training centers for instruction in aerial photography. Much valuable information would be gained about the performance of the equipment used and about the effectiveness of the technique used in its operation. It would be desirable to install such targets as soon as possible at training centers.

The level of resolution of photographs taken under operating conditions could be estimated to a reasonable degree by making a number of

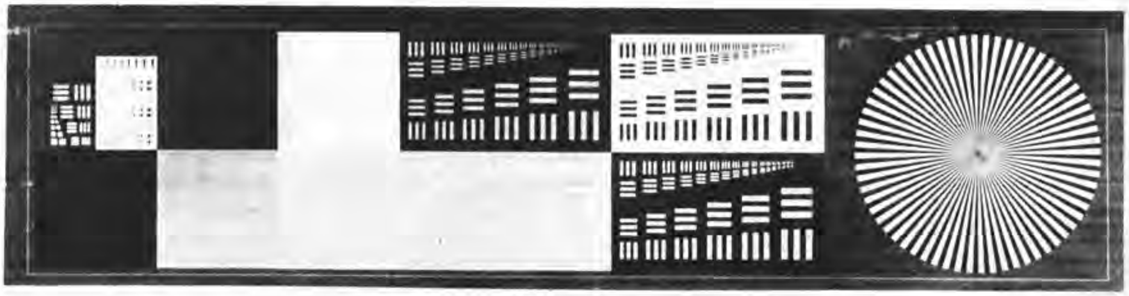


FIGURE 1. Large target at Orange.

photographs of a region containing a variety of common objects (trucks, airplanes, railroad tracks, buildings, ships, etc.) and also resolution targets. A series of photographs could then be selected which would represent known levels of resolution (5, 10, 15, 20, etc., lines per mm). By comparison with this test series, the resolution of any photograph could be estimated. The comparison should be made preferably between the negatives rather than between prints.

Extensive quantitative data on resolution with standard equipment was obtained on the NDRC-Wright Field Photographic Laboratory flight program using a standard 24-in. camera in the standard mount in an F-5E airplane. Seven missions were flown under this program during the summer of 1944. These tests, made over the Wright Field resolving-power targets, were flown at 25,000 ft.

Laboratory tests conducted at the Mount Wilson Observatory had previously shown that this lens was capable of resolving 25 lines per mm when used in conjunction with Super-XX film.[7a, 9] Analysis of the flight data at the Mount Wilson Observatory showed median in-the-air resolutions of 11.9 lines per mm across the line of flight and 11.4 lines per mm in the line of flight. This result was based on a study of 1,245 target images.

Although this result lumps together the data gathered using different f-stops and exposure times, and with no regard to the distance off axis, it is restricted to positions near the best focal setting and therefore may be regarded as a good indicator of overall average performance.

On the basis of these tests, the best performance of the 24-in. lens under ideal weather conditions is obtained at aperture $f/11$, exposure of $1/350$ sec. Longer exposure times increase the effect of image movement while the increased aperture required by shorter exposure times offsets the effects gained by use of this exposure. A summary of the results is shown in Table 2.

The results listed in Table 2 are based on selected target images, the selection rule eliminating from consideration all images obviously blurred by motions of the aircraft.

Although the probability of obtaining resolution in the air at half the value of laboratory performance is slightly less than one-half, individual photographs occasionally did show 25 lines per mm. It may be estimated that 2 per

TABLE 2. Average resolutions obtained with 24-in. standard camera at Wright Field, 1944.

Exposure time (sec)	Aperture	Resolution in the line of flight	Resolution across the line of flight
1/150	$f/16$	14.6	14.7
1/350	$f/11$	15.3	15.8
1/800	$f/6$	12.8	14.0

cent of the aerial photographs taken under the conditions of this test reach laboratory performance. This suggests that with standard equipment on fine days, haze, air turbulence, and other extraneous factors contribute relatively little to reduce resolution below the laboratory level of 25 lines per mm. Vibration is probably the chief offender. If this is correct, it is to be expected that laboratory resolution should be attained at occasional instants when the camera is momentarily free from angular motion except that which happens to compensate for aircraft translation.

The results of these tests are in good agreement with data gathered at Harvard[10] and by the Eastman Kodak Company[11] on similar tests at lower altitudes, using a B-17 bomber and an F-2 airplane with standard mounts. This indicates that the degree of departure of in-the-air performance from laboratory performance of the standard equipment is little affected by choice of aircraft, standard mount, or altitude.

2.4.1 Comparison of Performance of Standard Lenses with NDRC Lenses

The flight program conducted at Harvard in the summer of 1945 offered a comparison of in-the-air performance of four lenses.[10a] Figure 2 shows the frequency distribution of resolutions obtained with these four lenses: the 24-in. Aero-Ektar, the 36-in. $f/8$ fluorite apochromat, the 36-in. wide-angle telephoto, and the Harvard-NDRC 40-in. $f/5$ telephoto. Only target images recorded within 3 in. of the

[redacted]

center of the film were used in the data shown by these curves. This restriction limits the field to within 4.3 degrees of the optical axis for the 40-in. lens, 4.8 degrees for the 36-in. lens, and 7.2 degrees for the 24-in. lens. All the distribution curves have been normalized to 100 for maximum frequency; the number of observations used in the determination of each curve is given just above the location of maximum frequency on the abscissa. The angular resolution noted at the peaks of the curves is taken as the angle subtended at 10,000 ft, the altitude of the flights, by the center-to-center distance of adjacent white lines in the resolution targets. The left-hand curves for each lens show the distribution of resolution in the line of flight, the right-hand curves that across the line of flight. The full line contour used in the plot of resolutions of the 40-in. lens is derived from all flights with this lens over the resolution targets; the dashed lines represent the results of all flights except the last three of the

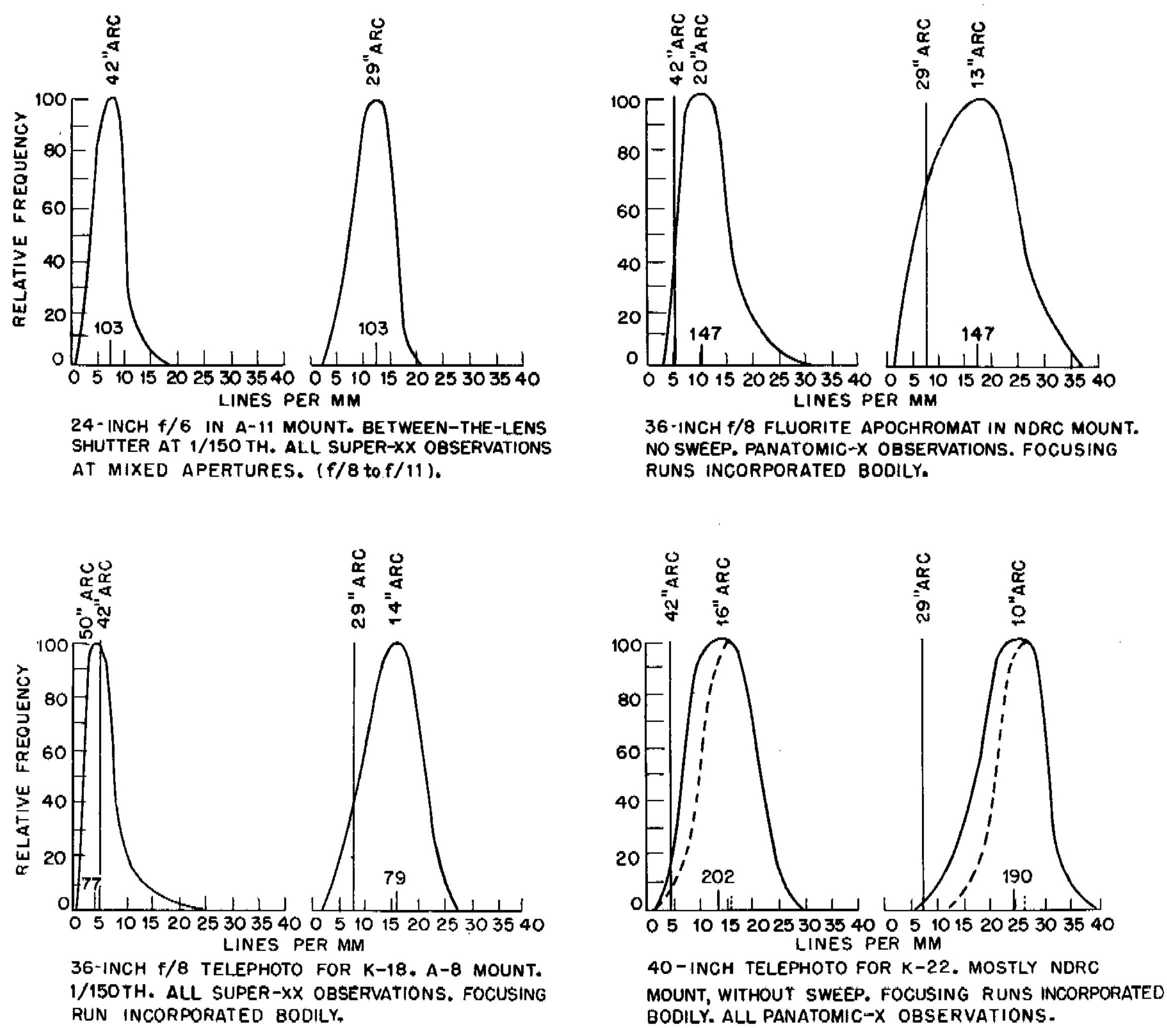


FIGURE 2. Frequency distribution of resolutions obtained with four lenses.

testing program. On these three flights the lenses were apparently distorted by a clamping device and results were of decidedly poor quality. It is felt that the dashed contour gives the more accurate picture of performance of the 40-in. lens.

For comparison purposes the angular resolution corresponding to the most probable per-

[redacted]

formance of the 24-in. lens has been scaled to the corresponding focal lengths and indicated on each of the curves. Thus, in the line of flight the 24-in. gives about 42 sec of arc resolution, as compared to 16 sec for the 40-in. Much of this difference arises from the exposure times. Across the line of flight, the 24-in. gives 29 sec of arc, compared to 10 sec for the 40-in. Again some of the difference can be ascribed to the exposure times used. If the 24-in. were used entirely at $f/8$ with yellow filter and $1/350$-sec exposure, its most probable resolution might reach 16 lines per mm or 22 sec of arc (see Table 2). The 40-in. at $f/5$ with Super-XX should yield about 22 lines per mm or 11 sec of arc. (See Chapter 1, Table 7.) Thus, the 3 to 1 difference in angular resolution might fall to 2 to 1 under circumstances more favorable to the 24-in. lens. Peak resolution, however, would still differ by more than 3 to 1. The $f/5$ working aperture of the 40-in. would then make this lens more versatile at high resolution than the 24-in. lens.

Results with the 36-in. telephoto and K-18 between-the-lens shutter in the line of flight confirm earlier predictions that unless sweep mechanism is provided, or unless exposure time is shortened, no appreciable gain in angular resolution over the 24-in. standard lens has been achieved, except for scale. Across the line of flight, the difference is about 2 to 1, whereas the focal lengths are only 1.5 to 1. The 36-in. would lose little on printing. With the 36-in. fluorite lens, the difference in angular resolution was about 2 to 1 in both directions. It should be pointed out, however, that photointerpreters regard a small decrease in graininess as a significant improvement in the quality of reconnaissance photographs. The increased scale of the 36-in. in effect gives this result by a reduction in the ratio of grain size to detail size.

In considering the other types of test patterns in the Orange installation, it is observed that the performance of the 24-in. Aero-Ektar lens is at about the same level of resolution for the standard pattern, the low-contrast targets, and the reversed standard pattern. On the other hand, the 40-in. telephoto gives lower resolution on the other patterns than on the standard pattern. This result is due to the larger amount of image flare present when using the 24-in. lens which results in less contrasty photographs than those taken with the 40-in. lens. For this reason, the performance in lines per millimeter of the 40-in. lens is more seriously impaired at peak resolution by the presence of haze and other factors that tend to lower contrast than is the 24-in. lens, but except under extreme conditions may be expected to yield superior results. It is to be expected that on the same emulsion, the difference in resolution, as recorded by two different lenses, becomes less and less with decreasing target contrast, and in fact the resolution numbers will converge at very low contrasts. At this point the problem becomes one of film properties rather than lens quality.

2.4.2 Comparison of Laboratory and In-the-Air Performance

The starting point of any study of the factors influencing resolution is to determine for any camera the gap between resolution in the laboratory and in the air. With a high-contrast target imaged on Super-XX film, the standard 24-in. lens resolves between 22 and 25 lines per mm in the laboratory.[7b] This lens cannot be used with finer grain emulsions because of speed limitations. Since Super-XX film is capable of resolving about 50 lines per mm at high contrast, it is evident these lenses must limit resolution to a serious degree. On the basis of the results of NDRC tests of standard equipment at Wright Field and Harvard, it was found that resolution of the standard 24-in. lens across the line of flight was about 50 per cent of its laboratory performance. (See Section 2.4.) Resolution in the line of flight was at a considerably lower level, due to the translational motion of the aircraft. The results of these two programs indicate that in-the-air performance is at a level comparable to laboratory performance less than 2 per cent of the time.

Laboratory tests at Harvard with the Harvard-NDRC 40-in. $f/5$ lens showed this lens to resolve at least 40 lines per mm on Super-XX film and 45 lines per mm on Pan-X film, using high-contrast targets. (See Chapter 1.) With

near perfect conditions, this lens can apparently reach the limiting resolution of the film, but it is felt that these conditions are not comparable with those encountered in flight test. The average resolution across the line of flight with the 40-in. lens in the Eastman-NDRC mount, at 10,000 ft over the Orange targets, was 22 lines per mm on Super-XX film, and 27 lines per mm on Pan-X film. This again is at a level of little better than 50 per cent of the laboratory performance, whereas this lens at no time attained laboratory performance in the air. Twice, however, 40 lines per mm were obtained on Pan-X. It is likely that haze and resultant loss of contrast, which proved unimportant for the 24-in. lens at 22 lines per mm, becomes a limiting factor for the 40-in. at 45 lines per mm.

There seems to be a striking gap between laboratory and in-the-air performance which must be explained and, if possible, eliminated. The study of factors which cause this gap and thereby limit resolution is complicated by the fact that many of these factors are operating simultaneously. As a result, special methods must be devised for isolating and evaluating each factor. Several factors have been considered and studied. There follows a discussion of these studies and the methods employed.

2.5 STUDY OF FACTORS LIMITING RESOLUTION OF AERIAL PHOTOGRAPHS

2.5.1 Lens Performance

On the basis of the discussion in the preceding paragraphs, although it is apparent that standard lenses do limit resolution, it seems unlikely that the resolution of the best available lenses is now an important limiting factor in aerial photography. While further improvement in lens design is to be desired, other factors are probably more serious in limiting present day resolution. (See Chapter 1.)

2.5.2 Translational Motion of the Aircraft

Reference to Figure 2 will indicate the difference between resolution in the line of flight and across the line of flight as determined by the Harvard tests. This discrepancy is due to image movement in the focal plane during the exposure, caused by the translational motion of the aircraft. Tests made by Eastman representatives[11a] at Harvard have shown clearly that resolution in the line of flight can be made of the same order as that across the line of flight by employing a sweep mount to compensate for image movement. In general, the performance of the Eastman-NDRC antivibration mount raised the overall level of resolution in aerial photographs by use of the sweep mechanism. The improvement in resolution across the line of flight by use of the sweep method of image movement compensation is shown in the plot (Figure 3) of the results of one of the tests conducted at Harvard.

Other methods have been devised to compensate for translational image movement. Harvard developed a unit consisting of two 10-in. diameter objective prisms rotating in opposite directions, but this device has not been flight tested.[8a] The British as well as Wright Field have developed a moving film magazine and also a rotating plane-parallel glass plate inside the camera. The performance of the sweep mount has, however, proved highly satisfactory in the compensation of ground movement. It would seem that this may offer a simple solution to the problem of image movement compensation.

2.5.3 Vibration

Apart from the effect of translation in the line of flight, vibration is probably the most serious factor in limiting resolution in aerial photography. The presence of vibration requires that short exposure times be used in all aerial photographs.

Such a requirement is generally met by using high-speed lenses and/or high-speed emulsions. There are obvious practical limitations in the construction of high-speed lenses of long focal lengths. However, the 40-in. $f/5$ telephoto lens might be considered as an approach to this method of solution and did, in turn, yield comparatively good results when used in conjunction with Pan-X film. The standard 24-in. lens

[redacted]

shows considerable loss in resolution when used at or near maximum aperture. The results of Table 2 show that this factor masks out any gain due to decreased exposure times. Further, this lens is not in itself fast enough to allow for the general use of any emulsion slower than Super-XX, in which case grain size becomes an important factor.

This combination of factors, the large-aperture lens and coarse-grain emulsion, demanded by the exposure limitations seriously limits the quality of aerial photographs. If, on the other hand, antivibration mounts are developed to allow for longer exposure times, present lenses in conjunction with fine-grain film would yield considerably higher quality results than those now obtained.

A study was made of the motions of aerial cameras in flight to evaluate: (a) the frequencies and amplitudes present in actual flight conditions, (b) the relative performance of standard equipment and NDRC mounts, and (c) the problem involved in design and construction of a stabilized camera mount for aerial mapping.

The method employed in evaluation of the magnitude of vibration was developed at MIT.[12] Trails of flashing lights were recorded on film at night by flying over a line of flashing lamps with open shutter. Early studies were made over neon lamps operating from a 120-c a-c line.

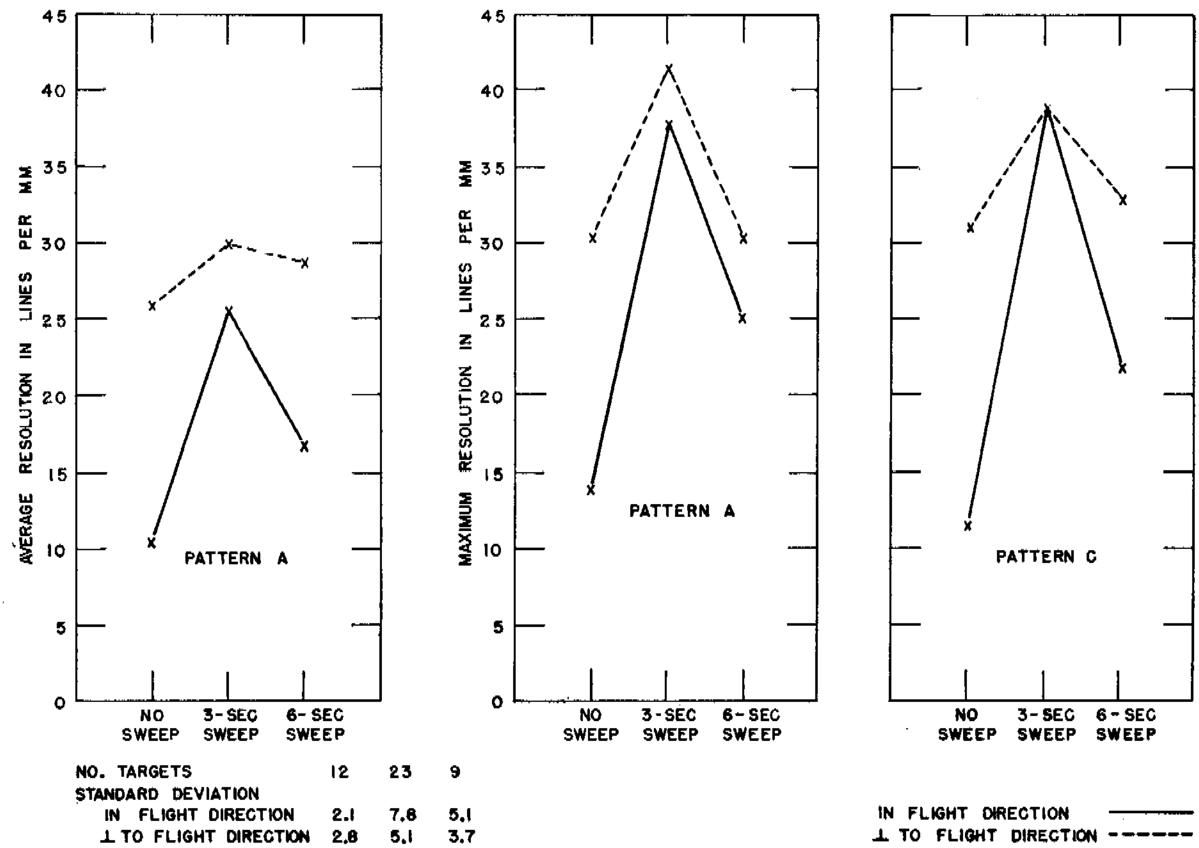


FIGURE 3. Effect of sweep on resolution.

Later work was done over special strobolux lamps designed to give flashes of $\frac{1}{7000}$-sec duration spaced $\frac{1}{60}$ sec apart. These lamps impressed a time scale in the form of a trail of dots over the film; the neon lamp images were separated by $\frac{1}{120}$ sec in time and successive strobolux images by $\frac{1}{60}$ sec. With this time scale, it was possible to interpret the data recorded on the film in terms of angular velocities of the camera in three coordinates—roll, pitch, and yaw. Straight level flight would be recorded as a trail of evenly spaced dots lying

in a straight line over the length of the film. Roll of the camera system would displace the dots, normal to the direction of flight (adopted as the y axis); pitch of the camera would cause irregularities in the spacing of the dots along the length of the trail (along the x direction), or in other words departures of instantaneous Δx's from the average Δx; while yaw would cause the line connecting the image of two lamps (widely separated on the ground but impressed on the film at the same time) to change its slope with respect to the coordinate system.

It was found that several characteristically different frequencies were always present in the trails. Arbitrarily, the long-period motions were assigned as overall aircraft motion. These were taken to include all motions with periods greater than 1 sec. Periods less than 1 sec were assigned to the camera-mount system.

Fifteen missions were flown at Wright Field in connection with the first vibration program and later fifteen other missions were flown out of Bedford on the Harvard project. Five of these Wright Field tests were over flashing lights, as were twelve of the Harvard tests. The rest of the missions were devoted to comparing mount performance over resolution targets.

Sixty-four night films were analyzed for vibration characteristics. The results of the first Wright Field test over the flashing lights are not representative of comparative mount performance due to the difference of location of the equipment in the aircraft, for on this mission seven different cameras were used in seven different mounts in seven different locations in a B-17. There is, however, considerable evidence on the basis of this test, in comparison with other tests, that the vibrational characteristics of the aircraft vary considerably from point to point within the ship. The periods were found to be of the same order over that portion of the ship tested, but the amplitudes of these motions were nearly twice as great in the bomb bay as in either the radio room or the nose of the aircraft.

With data from photographs taken with cameras located only in the standard position, the average median value of aircraft motion for the three B-17's used in the Bedford tests was found to be 3.7 mils per sec for the roll velocity and 1.9 mils per sec for the pitch velocity. These results come from the analysis of twenty-five films and are of the same order of magnitude from film to film, aircraft to aircraft, and day to day. Presumably these values represent motion of the fuselage itself.

Tests made at Wright Field with a fighter-type aircraft indicate that the average median roll velocity of the F-5E may be taken of the order of 6 mils per sec, while the corresponding pitch velocities are of the order of 3 mils per sec. Yaw motions act through a small radius on the film as compared to roll and pitch motions and hence are less effective in influencing resolution. The aircraft yaw velocities for both B-17 and F-5E are of the order of 3 mils per sec. On the basis of these results, it is concluded that aircraft yaw is relatively unimportant in limiting resolution in aerial photography.

On the other hand the median velocities of aircraft in roll and pitch are of such order as to impair the level of resolution of present standard equipment. As might be expected, the evidence points to the fact that lighter aircraft undergo more violent motions than do heavy bombers. In addition, the amplitudes of the motions of both aircraft are great enough to impose restrictions on mapping problems. It should be pointed out that in the event that vibrationless aircraft are employed in photographic missions, it will not eliminate this problem of overall aircraft motion.

For reference we should note that the angular motion of about 1 mil per sec will cause a 10 per cent loss in resolution with the 40-in. and 24-in. cameras at a $\frac{1}{350}$-sec exposure or that angular rates of 2.25 mils per sec with the 24-in. and 2.90 mils per sec with the 40-in. will produce a 25 per cent loss in resolution at this exposure. Bearing in mind that rates of motion are greater 50 per cent of the time than the average median velocities given above, it then appears highly desirable to develop a stabilized camera mount. The magnitude of the effect of aircraft motions will be even more serious with cameras of longer focal length.

Similar work on vibration carried on by the Sperry Gyroscope Company, using a gyro recorder, substantiates the above results. Gyro

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records made of the flights of a B-24, B-29, and a DeHavilland Mosquito bomber indicate that the B-24 behaves similarly to a B-17, a B-29 is more stable, and the DeHavilland bomber less so. British work shows the Wellington and the Sterling to be very stable aircraft, more so than our bombers.

In all cases, rolling motions are found to be more serious than the pitching of the aircraft, while yaw is negligible in its effect. Limited data point conclusively to the fact that manually controlled aircraft are subjected to lower angular velocities than are aircraft set on autopilot.

TABLE 3. Average median angular velocities (mils per second) of the camera-mount system.

Mount	Lens (in.)	Camera	Roll	Pitch	Approximate number of seconds of performance analyzed
A-11	24	K-17	2.97	1.56	18
A-11PM*	24	K-17	2.9	1.97	6
A-11BM†	24	K-17	3.4	2.6	3
A-8	24	K-17	1.79	1.51	15
A-27A	24	K-17	4.2	4.6	6
Eastman antivibration	24	K-17	4.42	4.42	6
A-11	40	K-22	1.88	1.66	3
A-11BM	40	K-22	2.6	1.6	3
A-8	40	K-22	2.75	2.79	15
Eastman antivibration	40	K-22	4.02	3.00	21
Center of gravity	40	K-22	0.99	0.67	12

* A-11PM indicates the standard A-11 mount with plywood spacers replacing the Lord pads.

† A-11BM indicates the standard A-11 mount with balsa-wood spacers replacing the Lord pads.

Table 3 summarizes the analysis of the short-period velocities as assigned to the camera-mount system. These results were obtained from analysis of films taken from a B-17. In each case, the camera was located in the same position, the outstanding variables from mission to mission being weather and pilot. Comparison of long-period aircraft motions from night to night indicate that the behavior of the plane was nearly the same on all missions. On this basis, it is felt that these results give a good indication of the average rate of travel of an image on the film when the mount is supporting the type of camera indicated. However, further studies should be carried on to expand the quantity of the statistical data and to measure the consistency of mount performance.

In determining the velocities assigned to the camera-mount system, the motions previously assigned to the aircraft have been taken out. In plotting the amplitudes of these vibrations, it is clearly seen that the high-frequency camera-mount vibrations are superimposed on long-period aircraft motions. The determination of total velocity at any point on the film, by the simple reduction method suggested in the preceding text, involves the sum of these two effects. To arrive at the pure camera-mount performance, the effect of the long-period motions must be removed. To do this, smoothed long-period curves were fitted to the amplitude plots. This smoothed curve was assigned as aircraft motion and subtracted from the total velocity. The residual was assigned to the camera-mount system.

The evidence indicates that the A-8 mount, of the mounts now available, gives the best performance for the support of 24-in. K-17 cameras and probably all 24-in. cameras except the K-18. When a heavier camera load (40-in. camera) is imposed on the mount, it appears, based on limited data, that the A-11 mount of the standard mounts gives best performance.

There is little difference in the performance of the A-11 mount whether Lord pads or solid plywood blocks are used as spacers.

Limited data available from the B-17 test made at Wright Field indicates that, in supporting a 24-in. K-18 camera, the A-11 and A-8 mounts both allow about twice the velocity on the film as when supporting 24-in. K-17 or K-22 cameras.

The performance of all mounts except the A-8, A-27A, and the Eastman mount is better in the direction of flight than across the direction of flight. The A-8, A-27A, and Eastman mount performed equally well in both directions.

With the selection of the proper mount for a given camera, it is evident that the long-period motions of the aircraft are more effective than those of the camera-mount system in impairing resolution.

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It is now possible to make a tabulation of the expected average resolution if mount vibrations were the only factor limiting resolution. (See Table 4.) The following tabulations are based on the assumption that the 24-in. Aero-Ektar lens will resolve 25 lines per mm on Super-XX film, and that the 40-in. $f/5$ lens resolves 40 lines per mm on that film. The data is arrived at by taking the reciprocal of the sum of the reciprocal of laboratory resolution and the travel in millimeters due to vibration during the exposures. This is, in effect, the addition of angular resolutions.

we should expect mounts, such as the antivibration mount, so damped as to transmit only low-frequency vibrations, to produce some pictures without trace of vibration, while nearly all pictures taken with a mount that transmits high-frequency vibrations will exhibit evidence of motion. This will be so even if both mounts have the same mean rotational velocity as determined by the above tests. It should therefore be pointed out that median angular velocity on the film should not be regarded as the only criterion for judging mount performance.

As is now planned, a very thorough investigation of relative mount performance over resolution targets will be undertaken at the Boston University Optical Research Laboratory during the summers of 1946 and 1947.

TABLE 4. Expected average resolutions if mount vibrations were the only limiting factor.

Focal length (in.)	Mount	Exposure 1/150 sec, resolution in lines per mm: In line of flight	Exposure 1/150 sec: Across line of flight	Exposure 1/350 sec, resolution in lines per mm: In line of flight	Exposure 1/350 sec: Across line of flight	Exposure 1/800 sec, resolution in lines per mm: In line of flight	Exposure 1/800 sec: Across line of flight
24	A-11	19	22	22	24	24	24
24	A-8	21	22	23	24	24	24
24	Anti-vibration	17.5	17.5	21	21	23	23
24	Center of gravity*	22	23	24	24	24	24
40	A-11	27	28	33	33	37	37
40	A-8	23	23	30	30	35	35
40	Anti-vibration	19	22	27	30	35	35
40	Center of gravity	32	34	36	38	38	39

* Based on vibration data for 40-in. camera.

On the basis of this tabulation, it is seen that mount vibration alone will not explain the observed loss of resolution, and, in fact, will not seriously impair performance at the faster exposure times now in general use.

There has been no adequate comparison of mount performance by resolution tests. One mission was flown by Eastman representatives while at Harvard. The conclusions of the report discussing that mission[11] indicate that the Eastman-NDRC antivibration mount gave better performance than the A-11 mount, contrary to the results listed in Table 3. Additional confirmation of this is found in further analysis of Harvard resolution tests which showed that the A-11 mount gave more consistent performance than the Eastman-NDRC mount but at a slightly lower level of resolution. It is true that

As is seen in Table 3, the performance of the center-of-gravity mount is far superior to that of any other mount tested. In the arrangement of this mounting, two 40-in. K-22 cameras were mounted symmetrically with respect to the center of gravity (see Section 1.6.6). Particular attention focused upon having focal plane shutter recoil and film winding opposed to one another in each camera. Such arrangement insured cancellation of shutter recoil effects during a photographic exposure and left the center of gravity of the system constant regardless of the amount of film used. The entire mass of the system was supported by a $\frac{1}{8}$ in. diameter

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hardened steel ball resting in a cup of matching radius in hardened steel. Figure 4 shows this mount supporting two 40-in. K-22 cameras. The widely employed in the problem of mounting aerial cameras. There is no reason to suppose that the quality of performance of this type of

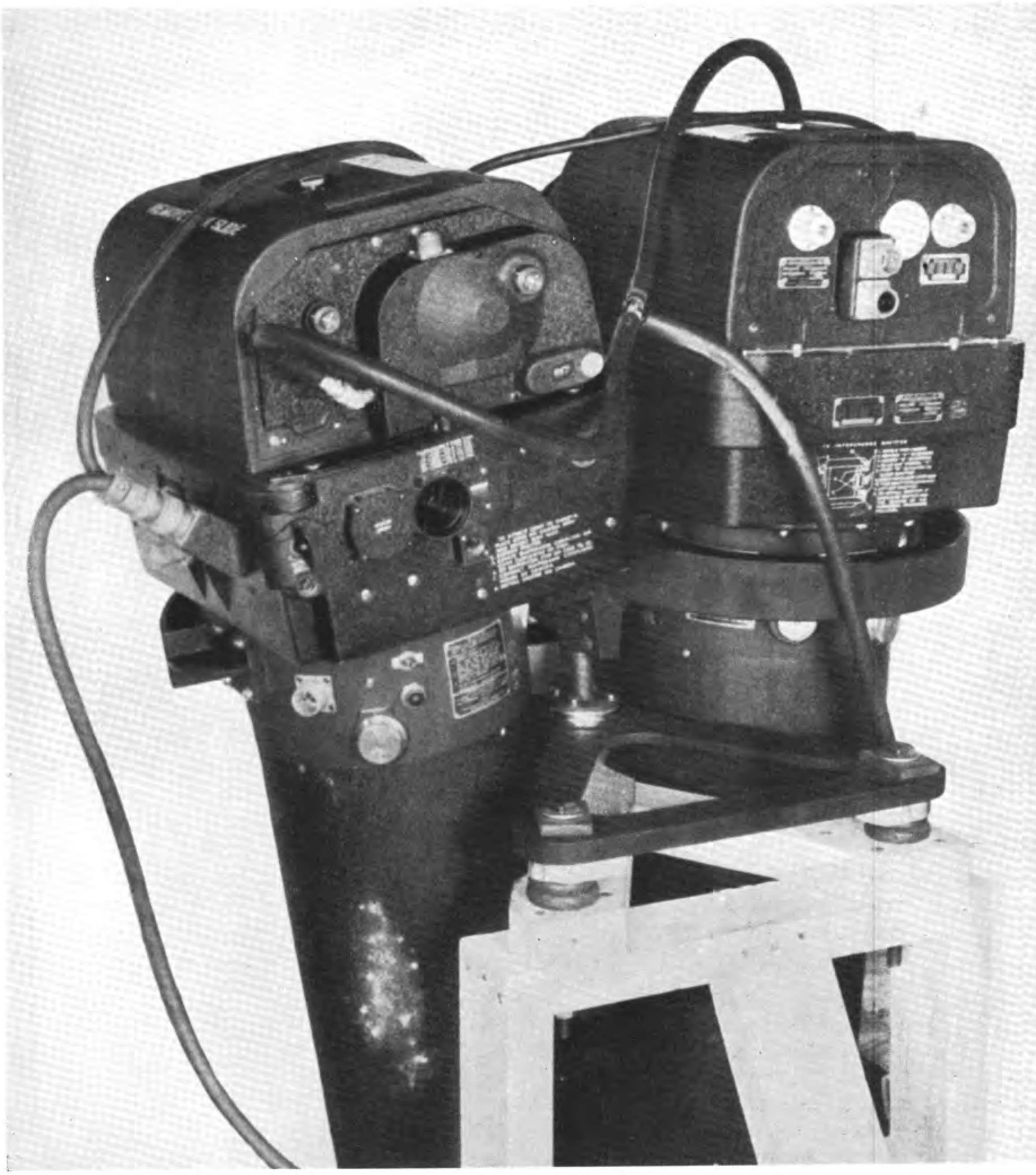

FIGURE 4. Center-of-gravity mount supporting two 40-in. $f/5$ K-22 cameras.

results obtained by the use of this mount in the vibration study confirms the thought that the center-of-gravity mounting principle should be mounting would change with the type of cameras employed. It has been stated that the relative position of the center of gravity and effec-

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tive point of support do not appear to be as important as the natural frequencies and damping of the mounting. It has been shown, however, that any mounting will be improved by bringing the camera center of gravity to the effective point of support. The results of the NDRC tests point out that the best camera mounting for minimizing the velocities transmitted to the film is at the present time a point suspension at the center of gravity of the camera system.

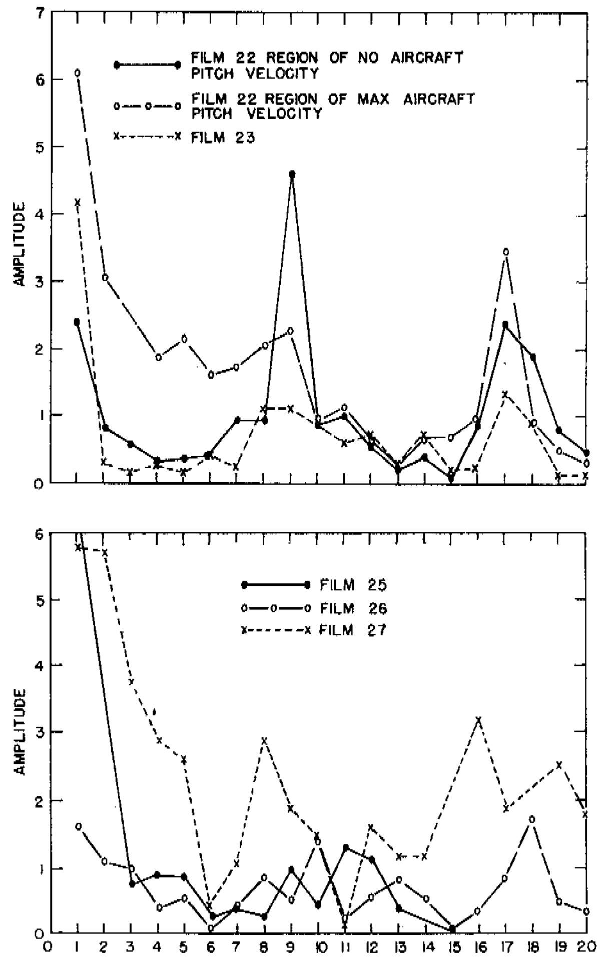

FIGURE 5. Plot of the first 20 harmonics of F-5E standard mount-pitch vibrations.

An attempt was made to compare the antivibration characteristics of the two center-of-gravity mounted cameras on the same path over the night targets. One camera exhibited twice as large median angular velocities as the other on the same pass. Assuming that the cameras were rigidly mounted so that they vibrated as a unit, the difference might then be ascribed to the vibration of lens elements in their cell or of the focusing bellows. There is, however, no definite evidence that this is a serious factor, but the usual clearance in a standard lens mount suggests that this factor may warrant further study. The magnitude of the entire effect is small and hence is not regarded as a limiting factor, being of the order of 0.5 mil per sec.

It was observed that the periods and amplitudes of the F-5E aircraft motions were distributed over a wide range, implying that the behavior of this type of aircraft is highly erratic. On the other hand, the heavier B-17's, on the basis of thirty-six films observed, exhibited very consistent characteristics, roll frequencies lying between 0.1 and 0.4 c (with one exception) with half amplitudes less than 6 mils (two exceptions) and pitch frequencies of the order of 0.3 c and half amplitudes of 1 mil with equally small scatter. It would, therefore, seem to be more simple to design a stabilized mount for use in a heavy bomber than in a fighter-type aircraft.

The characteristics of the high-frequency camera-mount vibrations were more difficult to determine due to the presence of overtones, but analysis clearly showed that the Eastman-NDRC antivibration mount transmitted the lowest frequency of all the mounts tested. These characteristics varied for the different types of cameras used in each mount, and in addition were further obscured by impressed beat frequencies attributed to the nonperfect synchronization of the engines of the aircraft, and the harmonics transmitted by the mount itself.

Additional work was carried out on large scale plots of the amplitudes of the roll, pitch, and yaw motions, both by harmonic analyzer and visual inspection to determine the amplitude frequency characteristics of these vibrations. As is clearly shown in Figure 5, the standard mount in an F-5E aircraft transmits to the camera two large amplitude pitch vibrations with periods of 0.13 and 0.06 sec. The press of time prevented a complete harmonic analysis, and, as it was found that the frequencies of the main harmonics could be determined

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by visual inspection to about as high a degree of consistency as that given by the harmonic analyzer, influenced as it is by the arbitrary choice of a fundamental, the further work was done by visual inspection. The quantity of data reduced has not been sufficient to yield other than the most general conclusions on this matter.

Another form of vibration present is that imparted to the camera by the shutter. Vibrations imparted by the focal plane shutter have been studied at Eastman, and by laboratory tests at Mount Wilson and flight tests at Harvard. In the Mount Wilson test,[7c] cameras were tested by taking photographs with the focal plane shutter and comparing these photographs with similar photographs made with external shutters, shutters completely detached from the cameras. Exposures with focal plane shutters gave the same resolution as exposures with external shutters. Exposures with between-the-lens shutters gave resolutions consistently less than exposures with external shutters, although the differences were small. In the Eastman tests,[11b] loss of resolution was observed when either type of shutter was used. The Eastman results are shown in Table 5. In-the-air investigation made by comparing resolution obtained on film exposed with the focal plane shutter traveling first in the line of flight and then across the line of flight give indication of a recoil velocity.[10b] Shutter recoil velocities necessary to explain observed losses in resolution in the air

TABLE 5. Effect of shutter vibration on resolving power.

	Relative resolving power	
	Horizontal lines	Vertical lines
Between-the-lens shutter		
1/50 sec	83	71
1/150 sec	81	73
External shutter	100	100
Focal plane shutter		
1/150 sec	92	82
1/350 sec	95	85
External shutter	100	100

are shown in Table 6. The magnitude of these results are in good agreement with the results of the Eastman tests.

Further study of this factor and incidently the ultrahigh frequency vibrations of the camera system was done by employing a rotor of twenty plain mirrors so oriented as to throw flashes along a row of fifty convex mirrors. The convex mirrors were placed to direct these flashes vertically up across the line of flight. By this device it was possible to impress dots on the film separated in time by $1/20{,}000$ sec.

TABLE 6. Shutter recoil velocities calculated from the observed resolutions.

	Recoil velocity in mils per sec
Camera rotated through 90°	
Resolution across the line of flight drops from 24.0 to 20.5 lines per mm	2.5
Difference between high and low tension shutters	
With image movement compensation, resolution in the line of flight drops from 23.0 to 19.5 lines per mm	2.8

These flashes were thrown across the line of flight and gave a record of angular excursion of the camera during the interval of exposure. The mass of data gathered through the use of this equipment has not been analyzed but the reduction of four photographs indicate a very significant amount of vibration due to the shutter and perhaps other factors during the exposure. The results yielded by this method are in good agreement with the values shown in Table 4. Figure 6 is a plot of image travel in microns as a function of time during ordinary exposures made using a focal plane shutter. These curves were determined from the mirror images.

Additional data were recorded on the night films to interpret loss of resolution as a function of angular velocity on the film. These data have not been reduced. A target used in this case consisted of opal-glass slits so oriented as to have their lengths correspond to widths of the lines of the standard resolution pattern.

By flying over these with open shutter, these slits were trailed along their narrow width and the entire length of the film gave in effect an infinitely long resolution unit. Excursions of the camera across the line of flight would tend to mar this resolution. By identifying corresponding points on the film, it would then be

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possible to evaluate loss of resolution directly in terms of the angular velocity at that point.

As is indicated by the data on vibration, the resolution of cameras in available mounts is definitely improved by reducing the exposure time as much as is permitted by the density re-

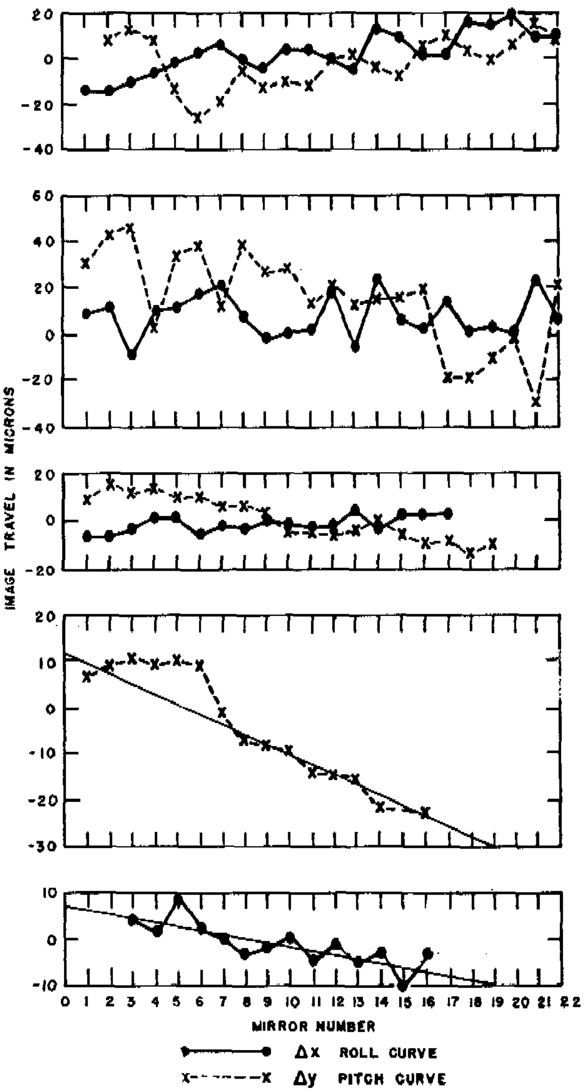

FIGURE 6. Image travel in microns during an exposure.

quirements of the negatives and the aberrations produced by increased apertures. In Table 3 it was indicated that the 24-in. Aero-Ektar lens gave best performance on Super-XX film at $f/11$ and $\frac{1}{350}$-sec exposure. Although a complete study to determine the optimum exposure with the Harvard-NDRC 40-in. lens was not undertaken, better results were obtained on Pan-X film at $\frac{1}{350}$-sec exposure at $f/5$ and $f/6.3$ than with $\frac{1}{800}$-sec exposure.

2.5.4 Focal Settings

The stabilizing of focus of the 40-in. $f/5$ camera by use of bellows for automatic focusing for changing object-distance and changing index of refraction of air with altitude, and in addition a thermostat employed for temperature control, is now paralleled by the use of heated and pressurized compartments in B-29 aircraft. This use of pressurized and heated compartments should be generally adopted for aerial photography with careful attention paid to the problem of convection currents. It would seem that hermetically sealed cameras set at laboratory focus should prove an ideal solution to this problem.

Cold-chamber tests at Harvard[2a, 4a] have shown that thermostatic control is essential if lenses with focal length of 40 in. or more are to give their full resolution. This is even more important when fluorite elements are used. With the present standard equipment, however, it has been found that laboratory setting of focal position is quite adequate. It was found that the use of a specially constructed optically flat photographic window stabilizes the position of focus and for that reason seems desirable. If airplane windows are to be used, they should either be made for the purpose according to acceptable specifications, or else, if selected from plate glass, be graded and marked. It is essential that long-focus and large-aperture lenses be provided with windows of suitable quality. Laboratory tests of selected plate-glass windows for use in an F-5E showed that a high percentage of the windows selected by visual inspection were of such quality as to lower the performance of the 40-in. Harvard-NDRC lens to the same level as that of the standard 24-in. lens.

A portable collimator with test target has been developed at Mount Wilson[7d] and a 35-mm micrometer film holder has been developed at Technicolor.[13] The combination is intended for use in checking the focal setting of commercial cameras and in determining the mean variation

of the setting from the optimum value under production conditions. This study could not be carried out under NDRC but would yield valuable information. The equipment is also capable of showing how accurately the optical axis is set perpendicular to the film.

There is evidence of local variation in resolution on many films. Often small areas appear to be out of focus, and in viewing successive frames it is noticed that these regions shift over the focal plane. This suggests that the standard vacuum magazine does not hold the film in good contact at all points, particularly at high altitude. Equipment has been designed to study this effect.[14] Time has not permitted making tests with this equipment.

The apparatus consists of sixteen identical simple lenses, mounted individually in focusing cells, symmetrically distributed over the 9x9 area for the A-5 magazine. Each lens was focused individually for a standard sodium source to give a sharp image approximately $\frac{1}{8}$ in. in front of the focal plane. In testing the film flatness, the sodium light falling on the film is in the form of a pattern of spots arranged around a circle of optimum diameter. Bulges in the film are manifest by smaller diameter circles. This Hartmann test forms a simple device for determination of film flatness.

2.5.5 Air Turbulence

Studies in 1941 at Mount Wilson Observatory were directed toward evaluating the effect of air turbulence on optical definition in air photography. A high-intensity flickering light source on the ground was photographed from an aircraft. Comparison of the definition of images on the film made from an aircraft with those made with the same camera at rest was used to detect the effect of air turbulence. On the basis of this study, there was no indication that air turbulence was a serious factor. Additional evidence, such as visual tests made in a low velocity wind tunnel and the occasional reporting of laboratory resolution on aerial photographs, gives clear indication that air turbulence with present equipment is a second-order effect.

With very long focus lenses, this may prove to be the limiting factor and hence warrants further investigation. Harvard tests of in-the-air performance of the 40-in. Harvard-NDRC lens, with and without an optically flat photographic window, showed little change in resolution, yet turbulence was considered as being diminished when the window was in place.

This test should be repeated using the 100-in. camera now being completed at Mount Wilson, for this camera should be more sensitive to air turbulence than any camera now in use.

Additional tests of air turbulence have been proposed. These include a periscope device for conveying light into the side of a camera body from a condenser system or a Kodatron unit to a resolution target in the periscope tube. At the end of the tube in the camera was to be a right-angle prism which directed the light toward the lens, so oriented that the light from the resolution target completely filled the lens aperture. A quartz mirror was to reflect the light back to the lens, the lens serving as an autocollimator. The resolution target image was then to be recorded on the film. The periscope tube was to be on a focusing mount for laboratory setting. The resolution target was to be stair-stepped in such a way that some one of the patterns would be in focus on the aerial film. The mirror to be used on this test was to be mounted in a streamline housing that could be lowered into the slip stream under the photographic window opening during flight. The mounting to minimize mirror vibration was to consist of hollow tubular braces supporting the streamline housing with solid rods inside these tubes, yet free of them, supporting the mirror itself. The loss in peak resolution when the mirror was lowered into the slip stream to allow 2 or 3 in. of air to stream over the mirror, compared to that when the mirror was inside the aircraft, was to be attributed to air turbulence.

2.5.6 Aerial Haze

The effect of aerial haze was investigated at the Mount Wilson Observatory.[9a] Photographs of distant ground targets were studied, and re-

duction of photographic contrast of these targets due to aerial haze was found to correspond closely to the reduction of visibility. The conclusions of these reports were that, when haze is noticeable, the resolution of a standard 24-in. camera is seriously limited.

Flight tests at Harvard, where loss of contrast of ground objects was measured, show that aerial haze is most effective in lowering contrast in the first few thousand feet of air mass. This is in good agreement with researches carried on by the Army Air Forces Photographic Laboratory at Wright Field. From the Harvard results, it was found that the magnitude of this effect is such that apparent target contrast may be lowered as much as 50 per cent at 10,000 ft. Above 5,000 ft, on the two missions undertaken, the loss of contrast drops off appreciably indicating that a layer of haze near the ground is most effective in lowering contrast and hence lowering resolution. Figure 7 shows target contrast as a function of altitude as determined on these two missions.

The method employed at Mount Wilson to evaluate the haze factor was to photograph two distant targets over a period of time which included widely different haze conditions. One target was light gray, the other dark gray. Each 5-ft square was placed about 6,000 ft away from the camera. The evaluation of haze was done by setting up a scale of 10, in which condition (10) indicated extremely clear, (9) very slight haze, (8) slight haze, (7) perceptible haze, etc. The resulting loss of contrast with haze was plotted. It is evident, based on their conclusions, that haze is a far more important factor affecting resolving power in aerial photography than is scattered light. If haze is sufficiently heavy, it becomes the dominant factor in limiting resolution in aerial photography. The reduction of resolving power due to aerial haze corresponds closely to the reduction in visibility.

Two other methods for the study of the haze factor have been suggested. Equipment was set up under the Harvard contract for these studies but time did not permit carrying out the investigation as planned. The first proposed test was to make use of a masonite resolution pattern illuminated by an Edgerton flash lamp for night resolution studies. This same target, housed in a roofless building to afford deep shadow, was to be photographed similarly in the daytime. The comparison of day and night resolution was to be regarded as a measure of the haze factor. The duration of the Edgerton flash would render the effects of vibration and

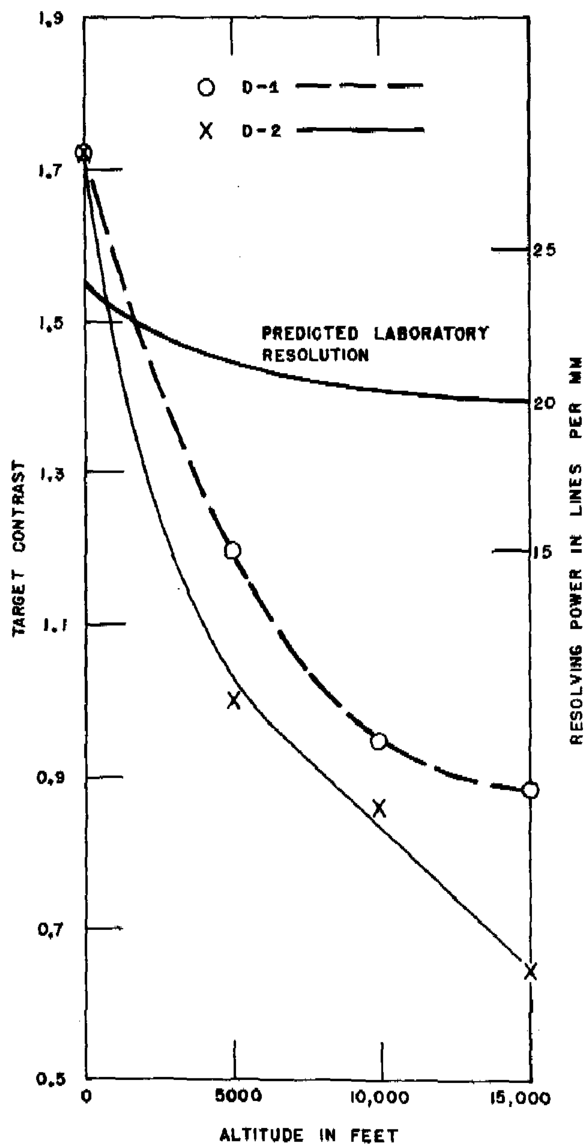

FIGURE 7. Target contrast as a function of altitude.

translation negligible. By this same method, a comparison of day and night resolution was proposed for shutter exposures of an opal-glass resolution target illuminated by transmission

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of the light from eighteen photo flood lamps set up for test. One night mission was flown over this target but target images were heavily overexposed and it was impossible to assess the film. It is now planned to continue these studies.

In daytime photography, one finds not only the light reflected from the target reaching the photographic plate, but also light scattered by particles in the atmosphere lying between the ground and the aircraft. This latter source of actinic energy is called "aerial haze." The night photographic methods proposed in the preceding paragraph are therefore free of this type of haze. As this light is scattered in accordance with Rayleigh's criterion, we find most of its energy concentrated in the blue region of the spectrum. Consequently, a considerable portion of the haze effects can be eliminated by use of yellow or red filters.

The effect of aerial haze is to lower the contrast of ground objects. This loss of contrast, in turn, results in a loss of resolution. As haze is a function of altitude, requirements are for higher contrast emulsions and development conditions the higher the altitude of the photograph.

At low levels of resolution in the air or in the laboratory, haze does not affect resolution as markedly as at high levels of resolution.[9b] Thus, the 24-in. Aero-Ektar lens which gives less contrasty pictures than does the 40-in. $f/5$ due to its large amount of flare has its level of resolution less affected by the presence of haze or low-target contrast than does the 40-in. lens. This was shown on the Harvard tests by comparing resolution of the lenses as obtained on the high-contrast and low-contrast patterns. The 24-in. lens gave nearly the same resolution for all contrast targets while the 40-in. lens, particularly on high-resolution photographs, gave considerably lower resolution values on the low-contrast target than on the standard pattern. Use of a black line target with white background found the performance of the 24-in. lens little affected by this reversal of line background reflectivities. The 40-in. lens gives lower resolution values on this pattern than on the standard pattern due to the scattering of background light into the line image, again confirming that the lens responds more sensitively to atmospheric haze than does the 24-in. lens.

The British have pointed out[15] that graininess is the most important factor limiting resolution of detail at low contrast in that resolution tends to the same value for a given film whatever the lens. As haze manifests itself by loss of contrast on the emulsion, it was considered important that all other factors producing this same or similar effects should be investigated. This was proposed, but time did not permit the carrying out of laboratory tests to evaluate these factors contributing to loss of contrast. The imperfections of the lens, lens flare, color aberrations, and poor focus, in addition to irradiation losses in the emulsion, contribute to this. Microdensitometer tracings, made of the photographic image of a ground target of eight equally spaced lines of decreasing line widths, showed an almost linear decrease of contrast (line to background) with line width. As this occurs quite markedly even for the high-quality images of the 40-in. lens, one may infer that resolution of fine detail not only demands high angular resolution but also must overcome the additional effect of loss of resolution due to the lowering of contrast of this fine detail on the emulsion.

This loss of contrast introduced by the film is a minimum for low exposure levels and for fine-grain emulsions. Employment of both these conditions markedly improves the level of resolution at the sacrifice of detail in the shadows.

The sharp qualities of image recorded by the 40-in. lens is a feature that does not manifest itself by comparative resolution figures. The use of the Harvard-NDRC 40-in. lens tends to decrease the magnitude of the scattered light thrown into the image compared to the performance of standard equipment. Thus the 40-in. lens shows greater contrast at all times, yet is subjected to greater relative losses of contrast by the presence of aerial haze than is standard equipment.

2.5.7 Scattered Light in Lens and Camera

Measures made at Mount Wilson[9c] indicate that the effect upon target contrast of light

scattered from the camera lens was of minor importance under normal conditions. Light scattered from the interior of the camera was found to be of no importance in the reduction of target contrast. In conjunction with these studies, the Mount Wilson Observatory made tabulations of resolving power as a function of target contrast. The conclusions from their work with the 24-in. Aero-Ektar lens are shown

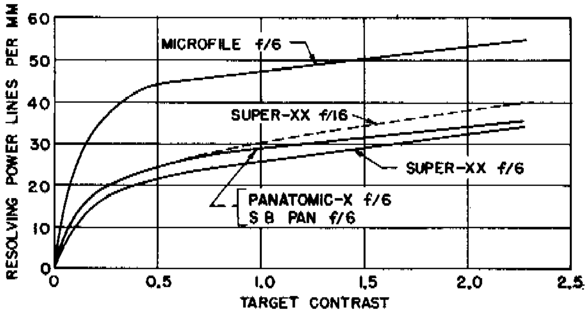

FIGURE 8. Resolving power as a function of target contrast.

in Figure 8. This experiment was made by using targets of different contrast. The conclusion from their work was that the amount of light scattered into the central part of the field by the 24-in. Aero-Ektar lens and the resulting reduction in resolving power is of minor importance under normal conditions.

2.5.8 Photographic Emulsions and Photographic Processing Techniques

For a given lens, the quality of a photograph is limited by the properties of the photographic emulsion. The standard practice of employing high-speed emulsions is the result of limitations of the light-gathering power of standard lenses and results in a relatively low level of performance. The practice of employing Pan-X, with fine-grain development process, in combination with the 40-in. $f/5$ lens has yielded a considerably higher level of resolution than has been heretofore obtained. As a result, it implies that fine-grain emulsion should be adopted for general use but the exposure requirements of such films require improved mountings and image movement compensations. Resolutions greater than 40 lines per mm have been obtained with the 40-in. with exposures of $1/350$ sec at $f/5$ and $f/6.3$.

The density of the negative affects resolution to a significant degree. Studies should be made to determine whether an exposure meter could be used to control exposure not only to improve resolution but also to include high lights and shadows within the range of exposure. Departures from standard processing techniques, particularly rapid development, will cause serious loss in resolution. On the basis of Harvard studies, it is recommended that a continuous processing development method be adopted. The uniformity of development by this method is highly desirable and will become more necessary when finer grain films come into general use. Although Smith tank processing gives no evidence of serious Eberhard effects, contrast is a function of distance from the end of the film in this method of processing.

With present methods of reconnaissance, it becomes necessary to make prints from the photo negatives. Investigations of the printing method[10c, 16] are in good general agreement. It was found that there is considerable loss of resolution on prints made with the standard diffuse printing box. Point-source printers employed at Harvard showed marked improvement in the level of print resolution, as did a parallel-light printer employed by the British. The diffuse printers were found to eliminate from the negative almost all the gain obtained by using better lenses and better mounts.

Loss of resolution by printing is probably the most serious obstacle today to the marked improvement of the level of aerial photographic reconnaissance. Limit of overall print resolution obtained by diffuse printing methods of aerial negatives seems to be of the order of 20 lines per mm. This would imply that the quality of prints from negatives resolving 22 and 45 lines per mm would be about the same. The maximum resolution obtained from a perfect negative by a diffuse printing process is about 30 lines per mm.[b]

An immediate study of this problem is in-

[b] More recent studies at Boston University indicate that resolution up to 60 lines per mm can be achieved under the most favorable conditions with the diffuse printing process.

[redacted]

dicated since improvements may offer an easy way to raise the level of resolution of present aerial photographic positives. Consideration should be given to the use of positive films to be viewed as transparencies, which would record a wider range of densities than is possible with paper prints. The method of precision enlargements of 1.5 to 2 diameters rather than direct contact prints from high-quality negatives would also seem to be capable of improving the level of performance. In this connection, it would seem that a great deal is lost if no assessments are made from the original negative of present high-quality photographs.

2.6 EVALUATION OF FACTORS

Approximate numerical determinations of the final resolution of a system are made by adding the reciprocals of the resolutions of each component of the system and taking the reciprocal of the sum. This method is used to weigh the factors that limit resolution in aerial photography. In addition to the limitation of lens-plus-film laboratory resolution, in-the-air resolution is affected by: angular motion effects that increase linearly with altitude; haze which introduces effects that increase with altitude but nonlinearly; translation which introduces an effect that varies inversely with the altitude, air turbulence, shutter inefficiency, effect of the photographic window, poor focus, and film processing which are considered as independent of altitude. Taking the average values of factors as given in Section 2.5 we calculate the resolution in the air. The adopted values are: (1) for the 10-in. lens, 45 lines per mm laboratory lens-film resolution on Pan-X film, an exposure of $\frac{1}{800}$ sec, altitude 10,000 ft, translation of 200 mph, pitch of aircraft of 1.9 mils per sec, pitch of camera-mount 3 mils per sec, shutter recoil 3 mils per sec in flight line, shutter vibration across the flight line of 1 mil per sec, roll of aircraft 3.7 mils per sec, roll of camera-mount 4 mils per sec, lens vibration 0.5 mil per sec, yaw 3 mils per sec, haze unknown, and other factors negligible; (2) for the 24-in. lens, 25 lines per mm laboratory lens-film resolution on Super-XX film, an exposure of $\frac{1}{150}$ sec, other conditions as above. We then tabulate the travel on the film during the exposure, add the rms of those terms that are regarded as introducing random motions, and add in the reciprocal of lens-film resolution.

From these data we can weigh the limiting factors. The good agreement of observed and calculated results should not be construed to imply that other factors, haze primarily, are negligible. Haze, when present, is a first-order limiting factor but its effects are marred by the presence of the other factors. Eventually, methods must be developed for minimizing haze effects. An evaluation of the average haze factor cannot be made on the basis of our present data, but an estimate of the weight of its effect is included by assuming that the difference between observed and calculated resolution across the line of flight is due to haze. The average photographic window, not used on these in-the-air tests, was taken to be as effective as haze in limiting resolution, probably a conservative estimate.

The data of Table 9 are to be regarded as giving only an indication of the order of magnitude of these factors that limit resolution. It should be viewed with consideration of the stated conditions of lens, aircraft exposure

TABLE 7. Prediction of effect of factors in limiting resolution of the 40-in. lens at 1/800 sec exposure.

	In flight line (mm)	Across flight line (mm)
Lens plus film	0.0222	0.0222
Translation	0.0375	0.0000
Aircraft motion	0.0024	0.0046
Camera-mount motion	0.0038	0.0050
Yaw (mount plus aircraft)	0.0004	0.0004
Lens vibration	0.0006	0.0006
Shutter vibration	—0.0038	0.0012
Total effect	0.0604	0.2910
Predicted resolution	16.6 lines/mm	34.5 lines/mm
Observed average resolution	16 lines/mm	27 lines/mm

Taking the same value for the factors, predicted resolution for the 24-in. lens at 1/150 sec exposure is tabulated. (See Table 8.)

time, and altitude before being employed to consider the relative magnitude of factors under other conditions.

[redacted]

2.7 RECOMMENDATIONS BY NDRC

Studies made during World War II on resolution of aerial photographs resulted in general improvement in equipment and in the photographs which were obtained. The entire subject can be placed on a sound quantitative basis as the result of complete studies of data accumulated under NDRC and as the result of further carefully planned studies.

TABLE 8. Prediction of effect of factors in limiting resolution of the 24-in. lens at 1/150 sec exposure on Super-XX film.

	In flight line (mm)	Across flight line (mm)
Lens plus film	0.0400	0.0400
Translation	0.1190	0.0000
Aircraft motion	0.0077	0.0147
Camera-mount motion	0.0112	0.0160
Yaw (mount plus aircraft)	0.0013	0.0013
Lens vibration	0.0019	0.0019
Shutter vibration	—0.0122	0.0037
Total effect	0.2089	0.0621
Predicted resolution	4.8 lines/mm	16.1 lines/mm
Observed average resolution	7.5 lines/mm	12.0 lines/mm

Aerial tests at the end of World War II showed that the best lenses then available, when used in the best available mounts, attain a resolution which is only about 50 per cent of that attained in the laboratory. This striking fact presents a challenge of great significance to all users of aerial photographs, and particularly to the Army and the Navy. There can be no doubt whatever but that a carefully planned program for improving resolution in aerial photographs will more than pay for itself in results, since at present it is necessary to use cameras with twice the focal length of those that could be used to give the same results if lenses, mounts, windows, and other accessories were brought up to adequate specifications. When each of the many factors which are now responsible for reducing resolution has been quantitatively evaluated, it will be possible to take stock of the entire situation, to state just what is required to reduce each factor to a specified extent so that overall performance may reach a certain level, expressed in terms of the resolving power, and finally to decide whether this result is worth the effort and expense involved. A compromise may well be indicated at a level somewhat below what is actually attainable, in view of the fact that the perfection of equipment and the cost involved rise rapidly as performance is improved.

Laboratory tests should be used to provide as large a part of the basic information needed as possible, so as to reduce to a minimum the need for flight tests. Flight tests are not well suited for isolating variables in a complex situation owing to the great variety of conditions which are inevitably encountered within any series of flights. Only in the laboratory can other conditions be held constant while one factor is studied. On the other hand, certain factors can be studied only in the air, and for this reason it is essential that facilities be available for extensive flight testing as part of the program.

TABLE 9. Relative weight of factors taken individually.

	40-in. lens 1/800 sec exposure in B-17 at 10,000 ft	40-in. lens 1/800 sec exposure in F-5E at 25,000 ft
Translation	10.0	10.0
Lens plus film	5.6	9.3
Aircraft roll	1.2	3.2
Aircraft pitch	0.6	1.6
Aircraft yaw	0.1	0.2
Center-of-gravity mount roll	0.3	0.5
Center-of-gravity mount pitch	0.2	0.3
Center-of-gravity mount yaw	0.1	0.1
Standard mount roll	1.0	1.6
Standard mount pitch	0.6	1.0
Standard mount yaw	0.1	0.2
Shutter recoil	1.0	1.6
Vibration introduced by shutter	0.3	0.5
Air turbulence (est.)	0.0	0.0
Average haze (calc.)	2.0	4.2
Average selected photographic window (est.)	2.0	3.3
Zero-power window	0.0	0.0
Lens vibration	0.2	0.2

Every effort should be made to attain accuracies in laboratory tests which are one whole order of magnitude beyond the probable effects of the factors concerned in the air. In the case of air turbulence, for example, it would be much more useful to know that at 300 mph, when photographs are being taken through a

certain window in the fuselage, resolution definitely cannot be expected to exceed 1 sec of arc because of turbulence, than merely to know that no effect as large as 5 sec of arc can be observed. Again, it would be much better to know that shutter vibration amounts to an amplitude of 0.002 mm during the exposure than to find merely that no effect is observed as great as 0.010 mm. Quantitative measurements of small effects are important because there are many such effects which are simultaneously at work to reduce resolution and these effects are additive.

A program of research in this field should include the points discussed in the following sections.

2.7.1 Laboratory Tests

1. Lens tests should be continued and extended in scope. They should be put on a strictly standardized basis after careful study of present results and after full discussion with all who are likely to contribute useful ideas. Parallel-line resolution targets should be used, and also a method which employs a neutral wedge to give a photographic record of the energy distribution in the image of a line source. Experiments should be undertaken to find out whether a useful test of resolution can be based on photographs of parallel-line patterns with a wedge placed in front of an image enlarged with a microscope objective. The lines would need to be longer in proportion to their width than those ordinarily employed. This method would yield energy distribution curves for the images of parallel-line patterns, from which it should be easy to determine, quite impersonally, the resolving power on the basis of a definition based on the contrast in the image of high-contrast parallel-line patterns of various spacings. The contrast used for defining resolution might be 10 or 20 per cent, for example. This method would eliminate the present uncertainties involved in reading resolution patterns, without adding any complex equipment for testing.

2. Resolution studies should be continued, based on accurate standardization of photographic procedures, absolute exposure times, a range of contrasts, and evaluation of lens performance by area.

3. Accurate studies of microscopic contrast as a function of line spacing should be initiated, making use of microphotometer methods, standardization of exposures, and intensity curves replotted on an enlarged scale.

4. Photographic emulsions should be studied extensively under the above conditions, to determine resolution with a perfect lens, with targets of various contrasts, and at various densities. These measurements should be made with various relative apertures. The results will make it possible to discuss on a quantitative basis the performance of lenses in the laboratory, and to infer the resolution that should be attained in the air in the presence of haze, if other factors did not tend to reduce resolution further.

5. Studies should be made to determine the effect on resolution of image movements of different rates. This should be done separately for each lens. The resulting data will show just how much angular motion can be tolerated in the air without reducing performance to a significant extent. This data is fundamental to the entire program, and present information is very limited.

6. Printing methods should be thoroughly investigated. Improved methods should be developed and introduced into general use. No method should be regarded as acceptable unless it retains in the print more than 90 per cent of the resolving power in the negative. An improvement at this part of the process is one which is least expensive to make, and can yield large returns. The effectiveness of a $1\frac{1}{2}/1$ precision enlarger for making paper prints with minimum loss of resolution should be investigated. Tests should be made of the performance of transparent positive film which may be markedly superior to paper for retaining resolution.

7. All promising shutters should be adequately tested for speed, efficiency, acceleration, recoil, and vibration.

8. Vibration studies should be made on all equipment that is normally used in close proximity to cameras to determine possible effects

on resolution. This should include magazines, sweep mechanisms, and servo equipment.

9. Mounts should be tested for transmissivity at all frequencies in the range that is encountered in aircraft for rotational and linear vibrations in each of three coordinates both separately and simultaneously.

10. Stabilized mounts should be tested for performance in restoring the camera axis after displacements of various degrees. Measurements should be made to show, after a disturbance, the angular rate of restoration relative to the true vertical as a function of time. Such tests should be made for disturbances of various angular rates. The accuracy with which the vertical is maintained should also be measured when the servo mechanism is attached to a vertical-seeking element. Although the maintenance of a true vertical is not necessary for improving resolution, it is very much to be desired for mapping purposes.

11. The focal settings of samples of commercial cameras should be measured when they are first delivered and again after various intervals of time in service to determine how accurately the settings are made at the factories and also the extent of changes that take place later.

12. Vacuum magazines should be tested under conditions simulating those encountered in service by using the device described in an OSRD report[14] at low pressure and at low temperature. If the film does not lie accurately in contact with the platen over its entire area at high altitudes, glass defining plates should probably be substituted.

13. Tests should be made of the effect of introducing glass windows of various optical qualities into the beam in front of lenses of various focal lengths as the basis for establishing a specification for quality.

14. The extent to which scattered light in various cameras reduces contrast, and thereby reduces resolving power, should be accurately measured. The effect of a lens cone and of coating the elements should be investigated. The effect on resolution of considerable dirt on the front surface should also be investigated to guide maintenance regulations.

15. The effect of air turbulence on resolution should be investigated by making experiments with optical glass windows in a wind tunnel.

16. The most favorable exposure level for maximum resolution over the entire negative should be determined, taking into account vignetting and the range of intensity within the image.

17. Cold- and pressure-chamber tests should be carried out to determine effects on focus, quality of image, and operation of equipment.

18. A device should be developed, for use with standard camera bodies, to permit precision focusing in the air.

2.7.2 Flight Tests

1. The frequency spectrum of vibration of the fuselage at the camera station should be determined by using a rigid mount (a) carrying a camera which photographs strobolux lights, and (b) carrying an optically recording free gyro. This is one of the most important parts of the program, since it provides data for laboratory tests of mounts.

2. From records of the angular motion of the fuselage, which is necessarily impressed on the camera mount, in each coordinate (determined as suggested under item 1), calculations should be made to predict the distribution of angular rates which would result if the mount were to have various periods and various amounts of restoring force and damping. The result of this investigation will show whether it is possible for a simple gimbal or spring mount with the most suitable values of period, restoring force, and damping, to reduce the mean angular rate of the camera, when exposed to the existing angular vibration of the fuselage, to a level which will not impair the resolving power of photographs with a lens of predetermined focal length. Unless the angular rate can be reduced by a simple mount to an innocuous level, there is need for developing a gyrostabilized mount. The mathematical study suggested is of fundamental importance in planning the entire program on camera mounts, and should be pushed through as fast as possible.

3. The angular vibration performance of various camera-mount combinations should be determined, using strobolux lights and also

resolution targets. The targets should include not only the usual painted parallel-line targets, varying in dimension by steps of $\sqrt[6]{2}$, but also trailed resolution targets at night having the same steps in size. Provision should be made for varying the intensity of the trailed targets to give optimum density.

4. The ultrahigh frequency spectrum of angular vibration should be determined by means of the rotor and row of convex mirrors, described in an OSRD report,[8] to evaluate the effect of exposure time on resolution and also the effect of shutter and other vibrations during the time of exposure.

5. The resolution of the standard 24-in. camera and of the Harvard-NDRC 40-in. camera, both in the standard A-11 mount and in the Eastman-NDRC mount, should be fully established by averaging the results of numerous flights. The results are of fundamental importance, since they will show how much gain in angular resolving power can be achieved by improving the camera and the mount very considerably, both separately and together. This result will do much to guide further efforts.

6. The extent to which resolution is improved with the 24-in. and with the 40-in. camera as a result of using the Eastman-NDRC mount without sweep, the same mount with sweep, and as a result of using the best stabilized mount should be determined.

7. Test patterns of various types should be compared from the point of view of significance and reproducibility of reading, as well as from the point of view of determining microscopic contrast in the image by using a microphotometer on the negatives.

8. The resolution given by strip cameras should be determined, using automatic rate control.

9. The extent to which haze reduces contrast, and thereby reduces resolving power, should be determined as a function of wave length and altitude on some of the best and some of the worst days for photography.

10. A study should be made of the correlation of resolution and of measured microscopic contrast as a function of line spacing with the ability of photointerpreters to identify objects on the ground placed close to the test patterns. Ordinary objects of various sizes should be used on normal backgrounds. Inexperienced observers should be compared with trained interpreters in these tests.

2.7.3 Specifications

1. Specifications for lens performance should be based on the results of further tests of resolution patterns.

2. Specifications for photographic windows should be based on tests made to show what quality is necessary for lenses of various apertures and focal lengths to prevent any detectable loss of resolution.

3. Specifications for camera mounts should be based on standardized tests on specified shake tables. The maximum transmissivity for vibrations of various frequencies, in each coordinate, should be specified.

2.7.4 General Recommendations

1. Studies should be made to establish the most effective combination of lens, aperture, shutter, exposure time, filter, emulsion, and mount for each focal length, using equipment now available.

2. On the basis of tests of the 100-in. lens, careful consideration should be given to the desirability of developing lenses with still greater focal length, employing folded optical paths.

3. A full study should be made of all Service problems, and equipment should be developed specifically to meet these needs.

4. Test targets should be installed at training centers to show what resolution is ordinarily attained with present equipment, procedures, and training. Examination of films showing these targets would serve as a stimulus to better work on the part of both staff and students, and would show the extent to which further development of equipment is indicated.

5. A special group should be trained in the technical details of operating and servicing precision photographic equipment. This group should have special squadrons of aircraft, with

[redacted]

precision equipment of the latest type, for its own exclusive use over special targets. They should report directly to a high level in the Army Air Forces, and should be in direct touch with laboratories where development work is in progress. In response to special requests, such a group could undoubtedly provide military information of great importance.

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Chapter 3

MAPPING METHODS EMPLOYING HIGH OBLIQUE PHOTOGRAPHS

By *Robert Singleton*[a]

UNDER PROJECT NA-124 investigations of equipment and processes for mapping from oblique aerial photographs were carried on. Two levels of accuracy were considered: reconnaissance sketching and large-scale topographic mapping. For various reasons the use of oblique photographs became necessary in World War II, but existing oblique reconnaissance methods gave insufficient accuracy, and no methods existed for large-scale topographic mapping from oblique photographs.

Instruments and methods were devised for using oblique photographs as desired, and were proved experimentally, but they had not been developed to the point of practical use in production when the war ended.

3.1 ORIGIN OF THE PROJECT

On December 11, 1942, the Hydrographer recommended to the Coordinator of Research and Development, U. S. Navy, that the National Defense Research Committee [NDRC] be requested to proceed with the development of the *Miller stereoscopic plotting instrument* and the *Miller single eyepiece plotter*. These were instruments for mapping from aerial photographs, which had been planned and partially developed several years earlier by the American Geographical Society.

Endorsed by the Bureau of Aeronautics, a request for Project NA-124 was forwarded to NDRC, which accepted it and assigned it to Division 16. Direction of the work was given to Section 16.1. In initial investigations by members of Section 16.1 it became apparent that broader views should be taken of the whole problem of mapping from aerial photographs, both near-vertical and high oblique.

On May 15, 1943, Contract OEMsr-1087 was concluded with Merrill Flood and Associates [MFA] of Princeton, New Jersey, to make a fundamental study of the problem. On June 1, 1943, Contract OEMsr-1039 was concluded with Aero Service Corporation, Philadelphia, Pa., as a companion contractor to provide laboratory and other facilities and to perform experimental work.

At the time of the Hydrographer's request, the Hydrographic Office faced two problems in the use of oblique photographs auxiliary to their regular mapping from vertical photographs. These were the extension of control through island groups and occasional plotting of shoreline information. See Sections 3.3.4 and 3.3.5. Although instruments and methods existed for handling both these problems, none was satisfactory for both precision and operational facility.

The best existing instrument for control extension was the *photo-alidade*, but its operation was cumbersome and required extensive horizontal ground control, which was a decided disadvantage. For shoreline delineation either the *oblique sketchmaster* or the Canadian *grid* method could be used, and had been used, but neither possessed the required precision and facility.

The *stereoplanigraph*, a German instrument, could handle both problems satisfactorily, but none was available. The only stereoplanigraph in the United States was owned by Fairchild Aerial Surveys in California, and it was in use continuously. From its plans the Miller stereoscopic plotter appeared to be satisfactory for both problems and to possess the precision and operational qualities desired. To a lesser extent the single eyepiece plotter also appeared to be satisfactory. No other equally useful instruments had been suggested, and hence the Hydrographic Office requested the construction of these two.

3.2 NAVAL MAPPING REQUIREMENTS

From the conferences and preliminary studies undertaken in getting the project under

[a] Aero Service Corporation.

way it became evident that the work could not be confined simply to constructing the instruments requested by the Hydrographer. Two facts were involved in this decision.

1. The development of the Miller stereoscopic plotter would be difficult because of the complicated mechanism involved and the precision required. Both it and the single eyepiece plotter appeared less suitable for the problems occasioning the request for reasons discussed in Section 3.3.2. Other approaches to solution of those problems promised to be more satisfactory. These are described in Sections 3.3.4, 3.3.5, and 3.3.6, and need no further attention in this section.

2. The Navy's mapping problems appeared to be much more fundamental than merely the use of oblique photographs. Activity in the Pacific was increasing rapidly, and most of that area was insufficiently mapped. To supply maps needed for the operations being undertaken, in time to be useful, was a major problem. It was later solved to a considerable extent by the capture of Japanese charts.

This problem became a major concern of the project from the start, but it was much more difficult to approach than were purely technical problems. While the studies of methods for control extension and delineation were going on, investigations of the type of maps needed and the problems of their supply were made. The activities in this connection occupy the rest of this section.

3.2.1 Brief Description of Naval Mapping Organization

The Hydrographic Office is the Navy's mapping (or charting) organization. It is concerned with other aids to navigation besides charts, and its extensive mapping activities include responsibility for charts of all water except the coastal waters of the United States. The latter region is the responsibility of the U. S. Coast and Geodetic Survey.

For its new mapping program the Hydrographic Office uses standard mapping methods, including ground surveys and photogrammetry with vertical photographs. Occasionally oblique photographs are used with the Canadian grid method. Before World War II, almost the entire map production consisted of navigation charts, and almost no topographic maps were made. During World War II the Hydrographic Office was called upon to produce large quantities of topographic maps for operation in the Pacific in addition to increased demands for navigation charts and new types of graphical presentations for landing operations, aircraft approach, and others. It expanded its facilities to provide for this new type of work and met the demands successfully.

The Hydrographic Office is a permanent organization in Washington. The Navy has no other mapping units located elsewhere, and no mobile trained mapping crews except a small number of survey ships which are primarily field survey parties operating under the Hydrographic Office.

3.2.2 Organization Requirements in World War II

In the exploratory investigation made at the beginning of this project many groups in the Navy were visited including the Hydrographic Office, Bureau of Aeronautics, Photographic Interpretation Center and Special Devices Division. The Army Engineer Corps was also visited. From discussions with the Washington personnel and with men recently returned from the Pacific it was learned that in many operations the maps were quite inadequate.

The chief reason given for this lack in some operations was the fact that there were no naval field mapping units. If an Army Engineer mapping unit were assigned to the operation, it could produce the necessary maps, provided photographs were available. If no such unit was assigned, as happened most often when the operation was chiefly naval, there was no naval counterpart to produce maps. There were almost no previously existing maps of the areas except, as discovered later, Japanese maps.

The second reason assigned was the frequent lack of vertical photographs, and the difficulty of obtaining them because of enemy action and

local clouds over the Pacific islands. Many oblique photographs were available, but there were no methods for mapping from them.

Attempts were being made to improve these conditions by teaching some elementary mapping to the naval photographic interpretation units and developing a crude method of sketching in plan from oblique photographs, which required no special instruments. While this certainly aided the photointerpreters to sketch the appearance of the target for briefing in air operation, for example, it made no contribution toward preparing the accurate maps needed for artillery bombardment and infantry operation. Accurate mapping techniques cannot be learned as a sideline.

The exploratory investigations uncovered a problem. In an attempt to learn precisely the requirements in maps (scale, accuracy, information to be represented, etc.) and the conditions of their use for Pacific operations so that recommendations could be made, several conferences were held through the Coordinator of Research and Development, attended by representatives from many service branches including those previously mentioned, amphibious and air operations groups in the Navy, the Marine Corps, and the Army field artillery.

At these conferences it was learned that, for artillery use, the horizontal accuracy required is the same as that for a chart on the 1/25,000 scale, i.e., 33 ft, and the vertical accuracy required is that of one-half a contour interval on a similar chart, i.e., 10 ft. For landing operations, underwater topography and large-scale topographic maps of the beach back to 500 ft from the water showing beach egress were essential. However, the requirements of such maps could not be given in detail. Accuracy of beach gradients, for example, and the critical beach gradients under various soil conditions for different vehicles, were not stated. It appeared that, although in Washington the problem was known to exist, sufficient information on which to base recommendations could not be learned.

To obtain this information, a party consisting of one representative of the Hydrographic Office and two from the Office of Field Service was sent to the Pacific. They went to Hawaii in May 1944, and learned that *all* new mapping for the Pacific Ocean area was done there under the authority of the Joint Intelligence Center, Pacific Ocean Area [JICPOA]. The cartography was customarily done by the 64th Engineers Topographic Battalion, located at Hawaii. Their method consisted chiefly of laying uncontrolled or partially controlled mosaics from vertical photographs and making planimetric maps at 1/20,000 from the mosaics. Information was added from time to time as more was obtained from later photographs. If contours were included they were compiled from other maps, estimated by aid of stereoscopes or drawn with Fairchild stereocomparators.

The accuracy required of maps for naval gunfire and inshore navigation was at least five times as great as that obtained. This was caused in part by the unsophisticated method used and in part by the photographs, which were taken primarily for intelligence purposes rather than mapping. The solution to these problems consisted of applying methods and knowledge already well known in the art of mapping.

One additional problem was found. At the time of the field trip, trimetrogon camera installations were being widely introduced in order to reduce the flying required for complete photographic coverage. In the trimetrogon camera installation three 6-in. cameras are mounted in an airplane so that one points vertically downward and the other two point out sideward at 30-degree angles of depression. No satisfactory method existed for using the two lateral (or "wing") pictures for large-scale mapping.

The findings[1] of the field party were, in summary, that the photographs, maps, and charts then obtained for the Pacific Fleet were sufficient for assault operations, except for naval and field artillery gunfire, navigation of landing craft, and troop operations throughout the initial engagement. They recommended that:

1. A program be instituted to consist of two parts which would increase mapping accuracy:
   a. Certain immediate changes in present methods.
   b. The prompt development and adoption of a mapping procedure specially de-

[redacted]

signed for the requirements in the Pacific, with special equipment designed to fit such a procedure.

2. More details be included on the maps which aid troop operation and navigation.

3. An immediate effort be made to find the best method of determining the depth of water.

Thus, the major cause of the inadequacy of maps, at least in the Pacific operations, was a lack of organized and trained personnel at the right places. The organization existed in Washington at the Hydrographic Office, but the time schedules of operations would not permit photographs to be sent to Washington for maps to be made there. One or several "Engineering Squadrons," fully equipped and trained in existing mapping methods, and located at the bases of operations, were required. Without such units no improved methods or equipment would be useful. With such units, headed by intelligent engineers, reasonably adequate maps could have been made from even the rather faulty material available.

3.2.3 Technical Developments Required

While many technical developments are needed in photogrammetric mapping generally, very few can be characterized as having been especially needed during World War II. The existing methods of mapping from aerial photographs were for the most part adequate for producing the maps needed, where applied by trained technical personnel. Three specific developments, however, which would have eased materially the problems encountered during World War II, are: aerial triangulation, photogrammetric sounding, and large-scale wide-field photogrammetry.

While these particular developments stood out, because of the geographic conditions encountered in World War II, as will be evident in the discussion which follows, they are no less important now that the war is ended. In the mapping that must now be done of the less well-developed areas of the world, the same conditions exist and the same problems must be solved if this mapping is to be done accurately and efficiently.

Aerial Triangulation

For mapping at large scales, the existing methods of photogrammetry require rather dense ground control. In the United States the ground control is provided by ground survey. In mapping such regions as the Philippines, the Pacific islands, and China, very little ground control existed, and there was almost no opportunity to send out field parties to provide control. The accuracy of the maps produced suffered thereby.

A method of providing accurate ground control from the air was required. How such a development should best proceed cannot be stated. One method would be the development of special photographic equipment of high precision and resolution, including cameras, photographic materials, and camera mounts.

No work was done directly on this problem during World War II, but the developments for stabilized camera mounts and improved aerial lenses carried on for other purposes might contribute to this development.

Photogrammetric Sounding

The necessity of knowing inshore water depths with great accuracy for amphibious operations is obvious. Only a few spot depths were known before World War II, and until near the end of the war the only methods available for obtaining depth were the usual ship sounding methods. Had aerial methods been available for obtaining accurate and complete soundings such losses as occurred at the landing on Tarawa might have been lessened.

The most promising methods for sounding are with low-altitude flying (about 500 ft altitude) using photography, as with the strip camera, or some variation of the radio altimeter giving reflections from both the top and bottom of the water. A satisfactory method employing the strip camera was developed at the Photographic Interpretation Center, and another was proposed by this project. They are described briefly in Section 3.3.8. Both came too late to be of much value.

Wide-Field Photogrammetry

Standard methods of photogrammetry use only vertical photographs for large-scale map-

ping. While high oblique photographs (and such photographs rectified) are dismissed as unusable, the historical trend in vertical photographs has ever been toward a wider field until now a 90-degree lens field is common. These two attitudes are inconsistent, since the inner region of a rectified oblique photograph is identical with the outer region of a vertical photograph, both taken from the same point in the air. The attitude toward oblique photographs most probably arose from the lack of any methods of handling them in quantity in the past. Obviously the criterion of utility should refer to the vertical angles of photographic images, rather than to the tilt of the camera at the time of exposure. Experiments made in this project indicated that at least a 120-degree field, symmetric about the vertical, could be used for large-scale mapping, and even greater fields for lesser accuracy.

The advantages of employing wider fields are: substantial reduction in flying, since each strip covers a greater area, and reduction in control necessary, since each photograph covers a greater area. Subsidiary advantages are the possibilities of control extension in island areas and photographing cloud-covered islands, mentioned in Section 3.2.2 and discussed in Sections 3.3.4 and 3.3.5.

Two ways of increasing the useful field are by developing aerial lenses of wider fields and by developing methods of mapping at large scales from oblique photographs so that multiple camera photography such as trimetrogon photography can be used. Work on wide-field lenses for aerial photography was done by Harvard University under another NDRC project. The development of methods for handling oblique photographs was carried on by the Geological Survey at Clarendon, Virginia, in developing the multiplex for using oblique photographs; by the Engineer Board, Fort Belvoir, Va. in the multiplex development and in rectification; and by this project of the NDRC in rectification and plotting.

The developments in this project are described in Sections 3.3.6 and 3.3.7. They came too late to be of use, but the multiplex development, although not fully completed, was used extensively by the Geological Survey in making maps of the Philippines and other regions.

3.3 TECHNICAL INVESTIGATIONS

3.3.1 Definitions and Fundamental Geometry

NOMENCLATURE

The terminology and relations used in the technical exposition are given here. Figure 1 shows two views in elevation of an aerial photograph at the moment of exposure, and other information. The position shown is that of the negative. The salient geometric quantities are indicated thereon, and their symbols and names are shown.

DEFINITIONS

Plane I is horizontal (axiom).
Line LN is perpendicular to plane I.
A is the distance LN.
Line Lp is perpendicular to plane II.
f is the distance Lp.
t is the angle between lines Ln and Lp.
Line Lj is the bisector of angle nLp.
Plane LH is parallel to plane I.
Plane P is the plane of L, n, and p.
Intersection of planes P and II is the "principal line."
The "scale" at a point such as b is the distance Lb divided by the distance LB'.
The scale of the photograph is f/A.

PROPERTIES

An aerial photograph is a perspective projection (perspection) of ground points, e.g., B, onto the plane of the photograph, as at b, except for distortion. That is, B, L, and b are collinear, except for small displacements of b due to many causes called "distortions."

A pair of lines lying in plane I, intersecting at J and including some angle a would be imaged on II as intersecting at j and *including the same angle* a. That is, j is a conformal point of the perspection (isocenter), and is unique unless I and II are parallel.

Scale at $j = f/A$.
Scale at $H = 0$.
Scale at $S = 1$.
Distance $jH = f \csc t$.
Distance $jS =$ distance JS.
If f and the location of p are known (from

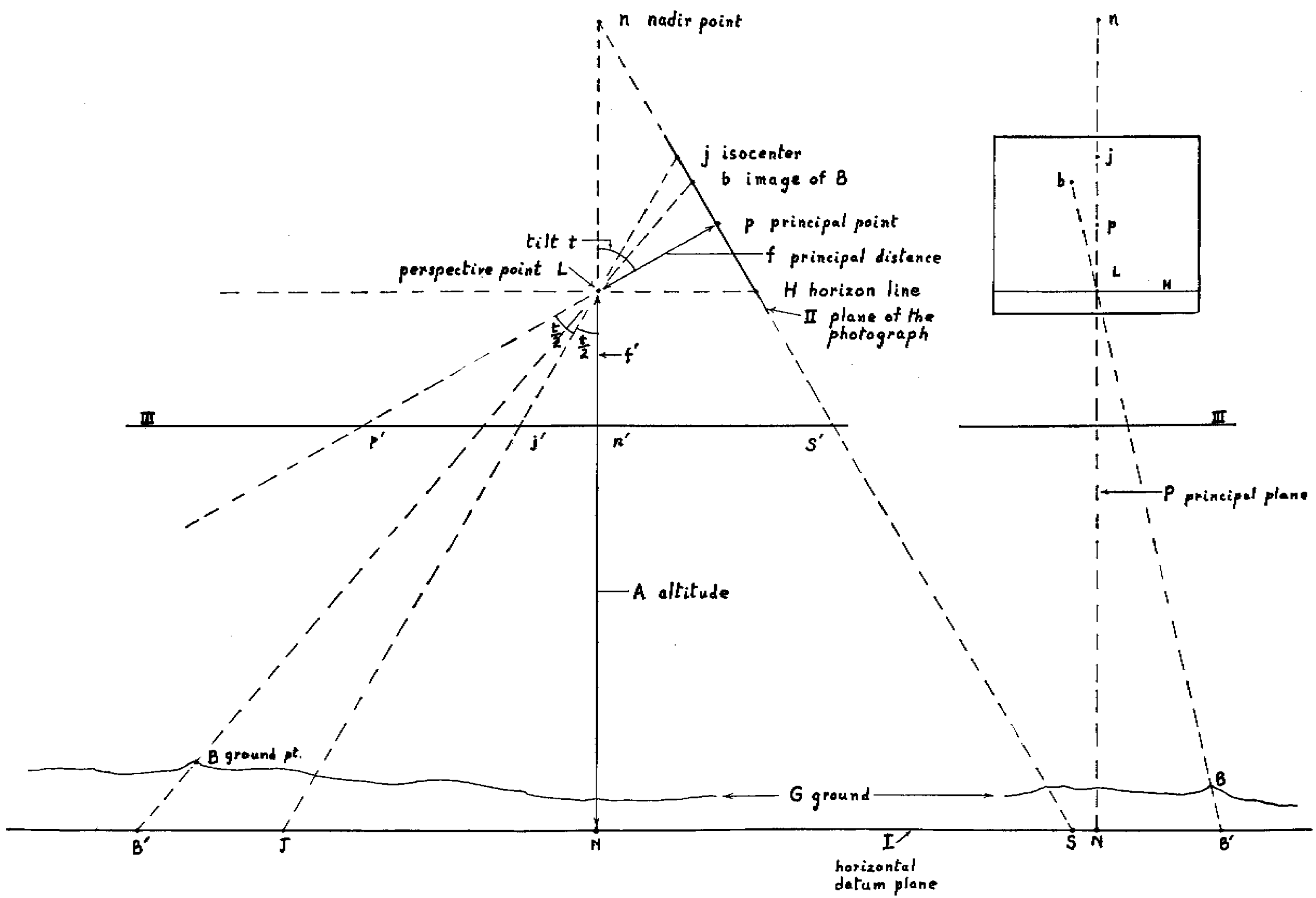

FIGURE 1. Geometry of aerial photographs.

camera calibration) and if the locations of any three points on the ground and their images on the photograph are known, all other quantities in Figure 1 may be determined.

If f and p are not known, the locations of five ground points and their images (not coplanar, and subject to conditions of noncollinearity) will determine the perspection, but in practice this determination is very weak, since the differences in elevation occurring on the ground are small, and it is not used. In fact, if the ground were a plane, e.g., coincident with I, the perspection would be indeterminate without knowledge of f and p, a *linearly infinite set* of perspections all giving the same image on the photograph. To determine this infinite set of perspections, four points are sufficient, and these determine the quantities $f \csc t$ and $A \csc t$, but f, A, and t are individually indeterminate.

Plane III represents a plane perpendicular to Ln. The image on III from a perspective projection of II through L onto III is called a "rectified photograph." It is apparent in Figure 1 that a rectified photograph looks the same, except for distortion differences, as would a vertical photograph ($t = 0$) taken from the same point in space if the field of the camera lens were large enough.

If the inverse perspection from III to II is considered in the same light as the perspection from G to II, then this is obviously equivalent to the case when the ground is plane. Thus, a linearly infinite set of perspections all give the same image. This is an important property and is used intensively in practical rectification.

A map is a drawing on a reduced scale showing the orthographic projection of landscape features such as shoreline, rivers, roads, buildings, and contour lines onto a horizontal plane. In mapping, the complete plotting operation requires the production of such a drawing from the representation shown on a photograph. For instance, an oblique photograph would show a vertical flag pole as a short line, but in an orthographic projection it should appear only as a point or small circle. The top of the flag pole is said to be displaced on the photograph because of relief. This displacement cannot be corrected from a single photograph but only by using two jointly.

3.3.2 The Miller Stereoscopic Plotting Instrument and Single Eyepiece Plotter

The essential parts of the stereoscopic plotting instrument as conceived are:

1. Two goniometers for holding a pair of aerial photographs taken from different points in space and overlapping in their views of the ground.
2. A pair of reference marks, which are points of light.
3. Two telescope systems for viewing the photographs from their perspective points, for viewing the reference marks, and for melding the views of the reference marks and photographs. As usual in stereoscopic instruments, each eye views one photograph and one reference mark through one telescope.

The goniometers have complete freedom of rotation about the perspective points. The pair of reference marks moves as a unit without rotation, but as a unit has freedom of motion in space. In addition, the distance between the reference marks may be changed, and the axes along which the marks move may be rotated with respect to the goniometers. All these motions have scales and vernier settings for measuring, recapturing, and presetting positions.

In operation a pair of overlapping photographs is placed in the goniometers and oriented to bring the entire overlapping region into stereoscopic fusion at once, as viewed through the telescopes. The photograph orientations necessary to obtain fusion are unique except for rotation of the pair as a unit about the line joining the perspective centers. When fusion is reached, the view corresponds geometrically to a view of the ground with the eyes placed one at each of the points in space from which the photographs were taken.

When the photographs are properly oriented the reference marks also fuse and appear as a single point of light moving three-dimensionally in the space model of the photographs. The axes on which the reference marks move may

[redacted]

now be oriented to the photographs to correspond in the stereoscopic model to a rectangular space coordinate system on the ground. This operation requires the equivalent of at least three control points in the model whose coordinates in the ground coordinate system are known. The axes are oriented so that, when the fused reference mark is placed in coincidence with a control point, the scale readings correspond to the known ground coordinates.

When this orientation has been achieved, the features of the stereoscopic model may be traced in horizontal projection by moving the fused reference mark along each feature, such as a road. The model may be contoured by keeping the fused reference mark at a fixed altitude and moving it so as to stay apparently always in contact with the ground. A stylus connected to the reference marks does the drawing. The stylus reproduces the horizontal movement of the reticle marks, but remains still when the reticle marks are moved vertically.

Since the stereoscopic model is a true representation of the ground, at some small scale, the drawing produced is a map of a small section of the ground. Many such drawings, made from many pairs of photographs, may be assembled into a sizable map.

There exist several instruments which perform like the Miller stereoscopic plotting instrument, although none is so well conceived geometrically. All are of foreign manufacture. Such instruments must be precise and are expensive. Highly trained operators are necessary, requiring at least a year's training before becoming efficient. The Miller instrument would be versatile, and is thereby well adapted to the use of oblique photographs where the demands are varied. On the other hand, it is expensive for only incidental use, and would probably not perform well unless used continually, because of the operator skill required.

The single eyepiece plotter amounts to one-half of the stereoscopic plotter, photographs being used in it singly. It consists of one goniometer, telescope, reference mark, and stylus. The precise relations necessitated in the stereoscopic plotter by having these parts in pairs are not required and therefore construction and use are much easier. Correspondingly, however, the stereoscopic model is absent. Versatility is much reduced and operation is more tedious.

The request by the Hydrographer, as a result of which this project was established, had been for the development and construction of one model of each of these instruments. The design and function of both were examined, and the use to which each might be put was investigated by conferences with the mapping and photographic branches of the Navy. As a result of this study it was decided not to develop either instrument.

The stereoscopic plotter was designed to be a precise instrument for making accurate topographic maps. It was intended primarily for use with vertical photographs, but could have been adapted to oblique photographs without great difficulty. Under conditions existing at the beginning of the project, the Navy would have had little use for the stereoscopic plotter since almost no topographic mapping was done.

The problems in the use of oblique photographs facing the Navy at that time were (1) extension of control between islands, and (2) tracing of shorelines from oblique photographs when necessitated by lack of vertical photographs. For neither of these problems would the stereoscopic plotter have been efficient. When, later, it was learned that topographic maps in large quantities would have to be made from trimetrogon photography, the method described in Section 3.3.7, employing rectification, was already well along in its development. Since that method promised greater efficiency and more rapid development, the stereoscopic plotter was not revived.

The single eyepiece plotter was designed expressly for tracing shorelines from oblique photographs and was readily adaptable to extending control from such photographs. Hence, this instrument was given serious consideration for these problems. Further analysis showed, however, that the single eyepiece plotter possessed no inherent superiority in accuracy or efficiency over completely graphical methods for extending control, employing only standard drawing equipment. As to the tracing of shorelines, experiments proved that greater accuracy and at least equal operational facility could be achieved with the pinhole rectifying camera, as

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described in Section 3.3.5. Development of this instrument, therefore, was also not undertaken.

3.3.3 Study of Photographic Quality

One of the first investigations to be undertaken in this project was a study of the characteristics and quality of oblique photographs. Almost all the photographs used by the Army and Navy in mapping were taken with cameras of short focal length (usually 6 in.) and wide field on Super-XX Aero Panchromatic film. Oblique photographs taken in this manner were characterized by excessive background haze, and their small scale made identification difficult, especially for control purposes. Little consideration had been given to other promising emulsions and to cameras of long focal length for the special purpose of oblique photographs for mapping.

Accordingly, a cooperative project was begun in August 1943 to obtain comparable photographs with various cameras and films. After some intermediate changes of plans, the locality finally selected was the group of four islands off the coast of Santa Barbara, California. An F-2 airplane was borrowed from the Chief of Intelligence, Corps of Engineers. The Bureau of Aeronautics, Division of Photography, loaned one K-17 camera with 6-, 12- and 24-in. cones and three F-56 cameras with focal lengths 8¼, 20, and 40 in. Aero Service Corporation supplied a 4-in. wide-angle camera and a photographer, and supervised the experiment.

The photographer made his headquarters at Mount Wilson Observatory, where photographic facilities were made available to him, and also facilities for testing and focusing the cameras. Photography began about December 15, 1943, and was finished the following February. It was carried out under various light and weather conditions. The film was developed in California and sent to the Aero Service plant in Philadelphia for printing and study.

Four Eastman films, Super-XX Aero Panchromatic, Shellburst Panchromatic, Infrared, and Microfile, were tried. The Shellburst and Microfile were specially coated for this experiment. The characteristics of Super-XX and Infrared are well known. Shellburst has finer grain, higher resolving power, and higher contrast than Super-XX, but only about one-third the speed. Microfile is a very much slower film with very high resolution. It proved to be too slow to record more than very faint images in this experiment.

The conclusions, from careful inspection of the photographs, but without quantitative analysis, were:

1. The superior haze-penetrating ability of Infrared film and the lack of serious offsetting disadvantages provides greater accuracy than that obtained from Super-XX whenever the area above the principal point in high oblique photographs is to be used.
2. The remarkable photographic quality given by Shellburst film merits its further consideration, especially for vertical photographs or foreground use of oblique photographs. Where background information is desired, it is inferior to Infrared.
3. Long focal length photographs on Infrared film can provide excellent control information, especially for extending position across water.
4. Microfile film is too slow for present aerial photography.

Some of the photographs were later used for testing the mapping method developed in the last phase of the project.

This study has been reported in full.[2]

3.3.4 Control Extension

In mapping island areas by means of vertical photographs it frequently happens that the water gaps between islands are too great to be included in a single vertical photograph. In this case, while each island may be mapped separately from vertical photographs, the islands cannot be related one to another and the scale of the individual island maps is unknown without extensive survey work on the ground. The water leaves gaps in the photography because the images of the water surface cannot be used, due to wave action and difficulties of identification.

In such an area, however, many islands may be included in a single oblique photograph. With adequate methods, the maps of individual islands made from vertical photographs can be related by using several oblique views. This is called "controlling the map."

One such area being mapped at the time by the Hydrographic Office was the Bahama Islands, and similar areas were expected in the Pacific.

While graphical methods already existed for control by high oblique photographs, none of these methods gave as great accuracy as appeared to be inherent in the photographs, and it was believed that by measurement and computation greater accuracy might be obtained.

Statement of the Problem

Control points in mapping are points whose positions are known relative to some coordinate system. Extension of control means the determination of positions for new points, which can then serve as control points, from existing control points. The purpose of this investigation was to determine the feasibility of extending control by computational methods and to compare the accuracy of such methods with the accuracy of graphical and instrumental methods.

For a computational method, coordinate systems are established on the ground and on the photographs. The general form of the transformation between points in the ground coordinate system and their images in the coordinate system of a photograph is assumed to be a perspective. The constants in the perspective transformation are parameters, varying with different photographs, and their numerical values for each particular photograph are not known a priori.

To determine the parameters numerically, control points must be used. Three control points are required to determine the transformation equations for each photograph. When this has been done, the equations may be used as computing formulas to compute the ground coordinates of other points from measurements of the photograph coordinates of their images.

The transformation equations are well known, being essentially the transformations of plane projective geometry. They may be written in many forms which are all algebraically equivalent and lead to exactly the same result if three control points are used. However, in any practical method it is desirable to use more than the minimum number of control points and to determine the transformation equation coefficients by some averaging process in order that the effects of errors of identification and measurement may be minimized. In this case the form in which the transformation equations are phrased and the averaging process used become important.

The problems in this approach are (1) to find a form for the transformation equations and an averaging process which lead to a sufficiently easy computation and to efficient estimates of the transformation coefficients, and (2) to determine by tests on photographs how large the errors of identification and measurement may be expected to be.

Analysis for the first of these problems was begun about June 15, 1943, and was completed by August 15 in form sufficient for first tests to determine the size of error.

A large number of photographs and other data, supplied by the Hydrographic Office, were selected for testing the method. Specifically, the material consisted of:

1. Almost complete vertical photographic coverage at 15,000 ft, of upper Frobisher Bay in Baffin Island with 6-in. K-17 cameras. Very many islands were included.

2. A triangulation net over the area, with stations identifiable on the photographs.

3. Oblique photographs of the area, at approximately 60-degree tilt, from 10,000 ft with 6-in. K-17 cameras.

It was necessary first to compute the coordinates of many points (minor control points) on the shorelines of islands, using the vertical photographs and the known coordinates of the triangulation stations (primary control points). This was done essentially by triangulation. Minor control points were selected, and both minor and primary control points were marked on all photographs on which they appeared. Coordinates of all points were measured on the photographs. Angles at the principal points of the photographs, subtended by the control points taken in pairs, were computed and were assumed to be the same as the corresponding angles on the ground. (Note the definition of *isocenter*, Section 3.3.1, and the proximity of j and p when t is small in Figure 1.) By resection and intersection, using these angles, it was possible to compute trigonometrically the coordinates of minor control points from the pri-

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mary control points. Many multiple determinations were included, so that an adjustment to reduce error could be made.

Minor control points were then identified on five of the oblique photographs, coordinates were measured, and the perspectives of the photographs were determined. As mentioned previously, three control points are sufficient to determine the perspective of a single photograph. An easier method, lending itself also to more accurate determinations, makes use of the photographs in pairs. The one used was such a method. It may be described briefly as follows.

From one photograph, suppose that lines are drawn through the lens from each of four image points. A four-sided solid angle results. Another such figure is formed from another photograph and the images on it of the same four ground points. These two figures may be oriented in an infinity of ways so that the edges of the solid angle of one intersect the corresponding edges of the other. For one of these orientations the points of intersection are coplanar. The complete figure can then be oriented so that the plane containing the points of intersection is horizontal. Note that the minor control points are at sea level, and hence coplanar. This completes the orientation of both photographs.

Four points provide the necessary number of conditions, but more than four points are desired to reduce error. As many as ten points were used in the test, with an averaging process. The general method itself is well known, but a unique feature of the particular procedure developed for this application was the computational ease of using excess points and averaging. The difficulty of computing increased in proportion to the number of points used rather than exponentially as is customary. A great many more points on each photograph were *not* used, so that the accuracy of the determination could be tested.

Coordinates for the control points reserved for test were then computed. Two sets of coordinates resulted from each pair of photographs. The mean position was used and compared with the coordinates found by triangulation from the vertical photographs. It was believed that this double determination would reduce the error below that of more customary methods in which a single position is found for each point.

Conclusions

A theoretical analysis of error was then made, assuming systematic error in f and p and uniform accidental error in identification and measurement of points on the oblique photographs. Interpreting the errors actually found in terms of the theoretical error analysis, the dominant source of error was found to be in identification of points on the photographs, which had a probable error ± 0.005 in. This is far greater than is customarily found with vertical photographs and is probably due to the extreme perspective.

In summary it was concluded that:

1. Since careful graphical work can be held to 0.005 in. accuracy, and is considerably easier, no advantage results from computation.
2. The possible reduction in error from the double determination is more than counterbalanced by the great magnification of errors in a direction parallel to the principal line.
3. Any method based on geometry similar to that used in this experiment would be unsatisfactory.
4. The graphical intersection methods using lines passing near the nadir point, in which the effects of errors parallel to the principal line are reduced, embody the most satisfactory geometry.
5. There is only a small possibility of such methods being improved much by substitution of computation for graphics.

3.3.5 Delineation from Oblique Photographs

In mapping from vertical photographs it is occasionally desirable to be able to draw shorelines and other features with considerable accuracy from oblique photographs. For example, a gap in the vertical photography may be covered in some incidental oblique photographs, or the most important portion of an area may have been covered with verticals, while outlying islands may show only in oblique views. Both of these cases occurred at Frobisher Bay in Baffin Island, which was being mapped by the Hydrographic Office at the time of this project.

Such circumstances occur more frequently in areas of military action than in friendly regions. The danger involved in repeat flights to complete coverage makes the full utilization of

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existing information of utmost importance. Fortunately, in areas of serious military action where incomplete vertical coverage occurs most frequently, oblique views taken for interpretation and intelligence are more frequent.

At the time of the investigation, the Hydrographic Office performed any necessary delineation from oblique photographs by use of Canadian grids, a process of drawing square by square from a perspective gridwork superimposed on the photograph to a square grid on the drawing board. This procedure is tedious and is less accurate than plotting with a good instrument. Hence a definite need existed for a satisfactory instrument to plot from single high oblique photographs with adequate accuracy.

For drawing shorelines and nearby features, locating islands, and sketching in the field without high accuracy, the relief displacement is not important. It is necessary only to remove the perspective distortion caused by the obliquity of the photograph. Hence, for this use it is sufficient to obtain from an oblique photograph a drawing such as might be made by tracing a vertical photograph taken from the same point in the air, if a vertical photograph of such great angular field could be made.

Preliminary Experiments

Starting in June 1943, investigations of possible types of plotters were begun. The principles considered as possibilities for use in such a plotting instrument were:

1. Photographic rectification, by projection of the oblique photograph onto photographic material
   a. through a lens,
   b. through a pinhole,
   c. from a point source of light.
2. Direct drawing, by
   a. viewing photograph and drawing board simultaneously, using a half-silvered mirror,
   b. projecting a point of light situated on the tracing stylus through a lens or pinhole onto the photograph.
3. Projection as in photographic rectification, but onto a drawing board for tracing, instead of onto photographic material.
4. Mechanical devices for continuously changing scale in the appropriate manner as between a tracing point and a drawing point.

The geometry is illustrated in Figure 1, where plane II represents the oblique photograph and plane III the required drawing.

Pilot experiments were made with the various principles, and tentative designs for possible instruments were tried in order to select the most promising. All the photographic rectification methods remained as possibilities. From the preliminary experiments it was learned that the major difficulty in rectification by projection through a lens lay in the great image distortion. With pinhole and point-light-source projection the questions were what image quality and speed could be achieved.

For direct drawing, the simultaneous viewing principle had already been used in practice in the oblique "sketchmaster." This device had many faults, including awkwardness of operation, parallax, and great differences in focus between the photograph and drawing. It was being improved and developed by several organizations, however, so no further attention was given it in this project.

Other principles for direct drawing appeared to be impractical. Available practical light sources gave insufficient light for projection by any means except a lens. Lens projection was subject to the same difficulty of distortion that occurred in photographic rectification using a lens.

It was finally decided to concentrate on the development of two rectifying cameras, one employing either a pinhole or a point source of light, whichever proved superior in subsequent experiment, the other using a lens or lenses specially designed to have tolerable distortion.

In subsequent experiments with wooden mockups many light sources and many photographic materials were tried. Reasonably good continuous tones and image quality could be obtained with the pinhole, certainly sufficiently good for tracing shorelines and major features near the shore, or for obtaining a quick sketch-map. The diffraction patterns in the point-light-source method were much more apparent and

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almost all detail was lost in solid blacks and whites.

With the pinhole camera employing a 0.01-in. hole, a reasonably short exposure could be obtained only if the image was received on fast film and an intense light, such as a carbon arc was used. Under these conditions exposure approximated ten minutes. The light distribution was far from uniform.

The point-light-source camera was therefore dropped. One pinhole rectifying camera was constructed by Aero Service Corporation under NDRC, and another by the Hydrographic Office. These are described in text that follows. A lens rectifying camera, which received its impetus in this investigation, also was constructed, but since it was ultimately put to more precise use it is described in Section 3.3.7 in connection with the MFA mapping method.

PINHOLE RECTIFYING CAMERA

The pinhole camera constructed by Aero Service Corporation is shown in Figure 2.

Item *A* is the light box, containing two Mazda AH-2 medium-pressure mercury-vapor lamps. The open side has an opal glass diffusion plate. The top has a light-trapped chimney, and in the bottom are openings to admit a forced draft from the blower *B*.

At *C* are two glass plates between which the negative is held. The negative is taped to one glass plate, in a position as if it were being replaced in the aerial camera. The other plate which has cut corners is then placed over the negative and the two are pressed together to hold the negative flat.

In the lens mount *D* is a pinhole of 0.01-in. diameter. The plane of the pinhole is perpendicular to the easel at the position shown in the figure. Its normal position is 6 in. from the negative, but this distance may be changed slightly by the wheel on the lens mount to match the focal length of the aerial camera if it is known more accurately. An 8¼-in. cone is also provided.

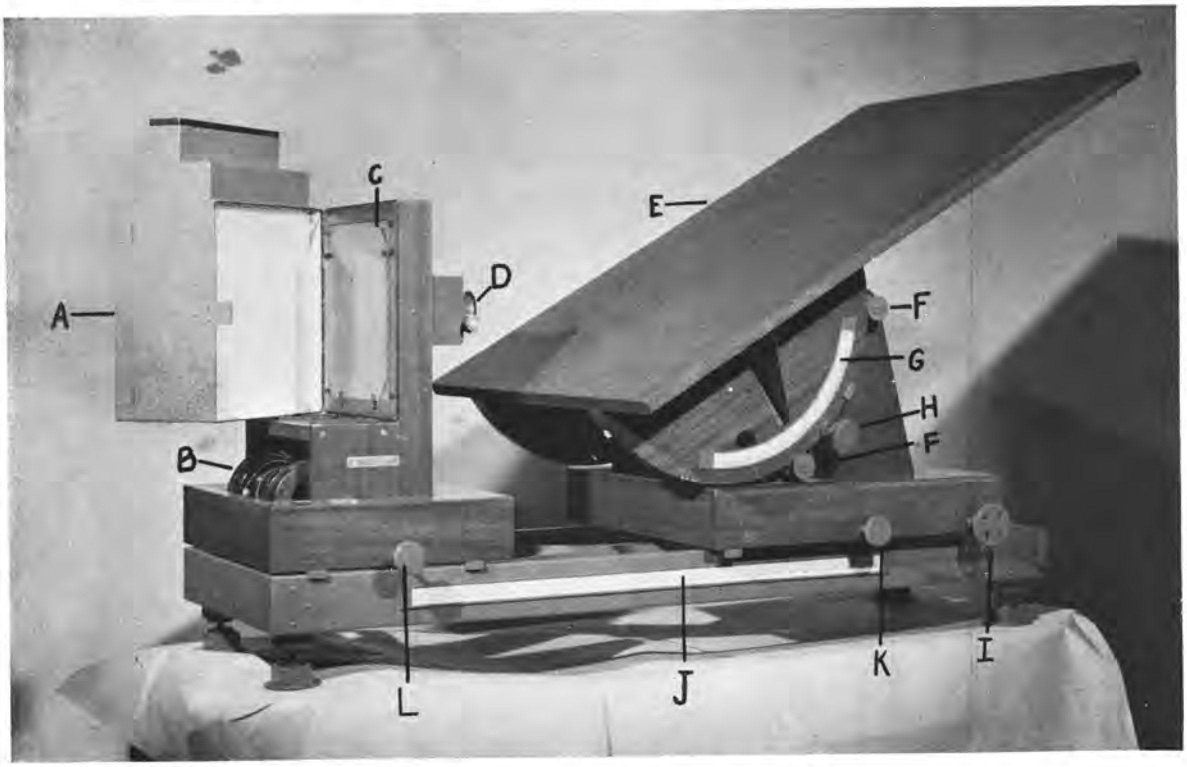

FIGURE 2. Aero Service pinhole rectifier

Item *E* is the easel, on which photosensitive material is taped. It represents the horizontal plane III in Figure 1. The easel moves on rollers *F*, is set by hand to the proper tilt as read on the scale *G*, and held by the clamp *H*.

The easel unit moves along ways on the base, to provide an enlargement setting. It is moved by a rack and pinion operated by the wheel *I*, set by use of the scale *J*, and held by the clamp *K*.

Another wheel *L* actuates a lock to hold the projection unit to the base after assembly. All parts are easily dismounted, and the camera is semiportable. Its

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size may be judged from the scale on the base, the white portion of which is 31 in. long.

A still simpler rectifying camera is shown in Figure 3.[b]

The negative or a tracing is taped to the back of the cone *A*, which is fixed for a principal distance of 6 in. No illumination is provided in the camera and the sun is usually used. The tilt setting is made by tilting the cone and clamping it in position at *D*.

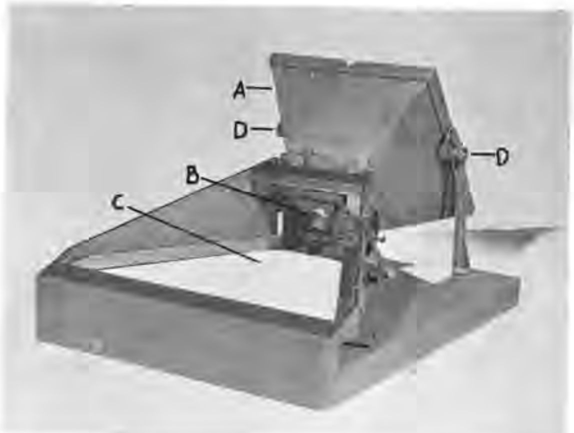

FIGURE 3. Hydrographic Office pinhole rectifier. (Courtesy Alexander Forbes, Commander, USNR, by direction of the Hydrographer.)

The pinhole is at *B*. Paper or film is taped to the base *C*, and a cover is provided to exclude extraneous light during exposure. No enlargement setting is provided, the perpendicular distance from pinhole to base being fixed at 2 in. Thus a reduction of 3× is imposed.

In a second model of this instrument the pinhole was replaced by the simple thin-lens system described in Section 3.3.6. The lenses were designed and manufactured by the Optical Research Laboratory, Harvard University (Contract OEMsr-474), especially for this use, and afforded a larger aperture and better image quality than did the pinhole.

PERFORMANCE

Performance data for the Aero Service pinhole rectifier and the first Hydrographic Office pinhole rectifier are lacking, since both these instruments were delivered to JICPOA without adequate preliminary tests. The second Hydrographic Office rectifier was retained at the Hydrographic Office and put to frequent use. The quality of the results is indicated by the following quotation:[3a]

The result is very satisfactory. Nearly all the discrepancies of over 500 feet, except in the far distance, are matters of photo-interpretation, due to difficulty in locating high water mark. Even in the case of Monument Island, which is 53,000 feet away from the Nadir in the photograph in which it appears, the distance is only 900 feet out.

It should be noted that none of these photographs afforded a sea horizon, only distant land of unknown elevation. This introduces the possibility of tilt error. Also tracing the shoreline by eye involves the possibility of significant error at distances beyond 4 or 5 miles. The results seem to show that the instrument is capable of mapping shorelines with fair reconnaissance precision very quickly.[c]

3.3.6 Lenses for Rectification

The investigation of means for delineating from oblique photographs, described in Section 3.3.5, led to the conclusion that photographic projection methods would be most accurate and easiest to use where standard darkroom facilities were available. The pinhole cameras were decided upon partly because of their relative simplicity in construction and operation and their freedom from distortion, and partly as an interim device to serve until a satisfactory lens rectifier could be built. These were intended only for reconnaissance, however, and for more precise work the greater speed and better image quality afforded by projection through a lens were essential.

Early experiments with commercial lenses by MFA, Aero Service Corporation, and other agencies indicated that speed and image quality were satisfactory, but distortion was excessive. Harvard University (Contract OEMsr-474), then undertook to design a lens especially for the rectification of high oblique photographs, possessing satisfactory characteristics with respect to speed, resolution, and distortion.

METHOD OF ATTACK

The following working specifications were adopted.

[b] This was designed by Commander Alexander Forbes at the Hydrographic Office and built at the Naval Gun Factory, Washington Navy Yard.

[c] Information supplied by Alexander Forbes, Commander, USNR, by direction of the Hydrographer.

1. The lens should be as fast as possible and should work at least at $f/50$ on the axis.

2. The lens should resolve 20 lines per mm, referred to the object plane.

3. Distortion due to the rectifying lens should not exceed 0.5 mm on a rectified photograph at unit scale with respect to the oblique photograph.[d]

The approach to the problem consisted of starting with the simple pinhole and testing successively more complicated lenses to find the simplest lens form that would satisfy the specifications. A test camera was constructed, and four lens forms were tested as follows.

Pinhole. Pinholes of diameters 0.010, 0.020, 0.028, and 0.040 in. were tested in three orientations, such that the plane of the pinhole was inclined 0, 30, and 70 degrees to the image plane.

Simple Lens. This lens actually consisted of two very thin plano-convex lenses cemented with the plane sides in contact, and with a central stop. Tests were made with 0.028-, 0.040-, and 0.100-in. apertures, with the plane of the lens parallel to the negative, and with the plane of the lens passing through the intersection of the object and image planes in the correct orientation for first-order geometric focus. One test was also made with the lens plane parallel to the negative and the plane of the aperture stop passing through the intersection of the object and image planes.

Spherical Lens. This was a centrally symmetric spherical system with a central stop. Since a single spherical lens would have been bulky a lens was constructed with an outer spherical shell of EDF-3 and an inner spherical shell of C-1 glass. It was tested with apertures of 0.020, 0.028, and 0.040 in., and in the two orientations described for the simple lens.

Hypergon Lens. The Hypergon lens consists of two very steep thin meniscus lenses about a central stop. The optical data for the lens used in testing resolution (focal length 3.464 in.) were:

Surface	Radius	Separation	Index	Glass
1.	0.3550 in.	0.0834 in.	1.62867	DBC-1
2.	0.3565 in.	0.574 in.	1.00000	
3.	—0.3565 in.	0.0834 in.	1.62867	DBC-1
4.	—0.3550 in.			

[d] For definition of the scale of a tilted photograph see Section 3.3.1.

Apertures of 0.050, 0.080, 0.100, 0.150, and 0.200 in. were tested with the lens in the position and orientation required for first-order geometric focus.

RESOLUTION TESTS

For determining the resolution obtainable with the optical systems to be tested, a simple rectifying camera was constructed at Harvard. This camera was similar in conception to the Hydrographic Office pinhole rectifier illustrated in Figure 3. However, the angle between object and image planes was fixed at 60 degrees, and the point of projection was 6 in. from the image plane as well as from the object plane.

Illumination consisting of a tubular mercury-vapor light source parallel to both object and image planes was provided and condensed on the projection lens by a cylindrical lens system. The light source and condenser were mounted on rocker arms pivoted on an axis passing through the projection lens. Thus, the illuminator could be moved to illuminate any part of the object, and the great variation in illumination required at different portions of the object could be achieved by moving the illuminator rapidly near the isocenter and slowly near the horizon (respectively j and H, Figure 1).

For determination of resolution, twenty-eight high-contrast resolution targets were mounted on a glass plate in the object plane, in seven rows of four each, running parallel to the horizon. The targets were about 1½ in. apart in the rows, the first target in each row lying on the principal line. The first row passed through the isocenter, and the seventh lay at about 75 degrees off the vertical. The positions and assigned members of the targets as projected on the image plane are shown in Figure 4.

The projected images were received on blue-sensitive glass plates laid in the image plane. The resolution determined from the images was recorded as lines per millimeter on the object plane. The values of the best average resolution obtained with each of the four projection systems tested are shown in Table 1.

It is evident that the simple lens and spherical lens were better than the pinhole, that the spherical lens was no better than the simple lens, and that the Hypergon was far superior for uniformity of coverage and resolution. In

fact, the performance of the Hypergon was adequate, and so no more complex lenses were designed.

At targets 1 to 4, the projection was approximately 1/1, and 23 lines per mm were resolved. When the resolution of the Hypergon as incorporated in the two-stage rectifier (see Section 3.3.7) was measured this result was verified. In that rectifier, however, the isocenter region was reduced 1.8× in each stage, and at that reduction ratio only 14 lines per mm on the object were resolved. In two stages, 8 lines per mm on the first object were resolved on the second image. In the region near the horizon, 40 lines per mm on the object were resolved. Thus, the final rectified print maintained approximately average resolution, and inspection of the photographs showed no loss of quality from original negatives photographed with a 6-in. Metrogon lens on infrared film.

TABLE 1. Resolving power of four projection systems (lines per mm on the object).

Target	0.020 in. pinhole		0.040 in. thin lens		0.020 in. spherical lens		0.10 in. Hypergon	
1	1.1	1.1	5	10	5	7	23	23
2	1.1	1.2	5	8	5	5	23	23
3	1.1	1.4	3	4	4	5	20	20
4	1.1	1.7	2	2	3	3	20	17
5	1.3	1.3	7	10	7	8	23	20
6	1.3	1.3	7	8	7	7	27	27
7	1.2	1.4	4	5	5	5	27	20
8	1.2	1.4	3	2	5	3	25	17
9	1.4	1.4	8	10	8	8	30	30
10	1.5	1.5	8	10	7	7	23	23
11	1.4	1.4	7	7	7	6	27	23
12	1.4	2.0	5	2	6	4	27	20
13	1.9	1.4	10	10	8	10	33	30
14	1.5	1.4	8	9	8	7	30	27
15	2.0	2.0	8	7	7	4	27	20
16	2.2	2.2	8	2	7	3	23	20
17	2.0	1.3	10	9	8	10	30	27
18	2.6	2.0	10	10	8	8	27	27
19	2.6	2.3	10	8	8	6	23	23
20	3.3	2.3	8	2	7	4	23	14
21	4.0	2.0	10	10	8	10	23	30
22	5.0	2.0	9	10	7	8	23	30
23	4.0	2.4	10	7	7	5	20	23
24	3.3	3.3	4	1.5	6	5	10	17
25	3.3	2.7	8	10	7	9	17	27
26	3.3	2.7	8	10	7	8	13	30
27	3.3	2.8	4	4	5	6	13	23
28	2.5	2.5	2	2	3	4	...	...

DISTORTION TESTS

The image distortion in rectification using the Hypergon was not determined experimentally at Harvard University, but it was computed on the basis of the lens design. By this computation the image distortion should not exceed 0.5 mm in rectification of a 60-degree oblique, 6-in. photograph at 1/1. The maximum amount occurs far out near the horizon, at about 78 degrees vertical angle. Thus, the Hypergon lens design meets the distortion specifications adequately.

The first 4.402-in. Hypergon delivered to MFA was tested extensively for distortion in the two-stage rectifier. Distortion of 0.2 to 1.0 mm was found in various images, although in this design a maximum net distortion of only 0.05 mm was expected. The variation in distortion was found apparently to have arisen from bending of the plates by the plate clamps. However, further tests indicated with reasonable certainty that distortion of at least 0.2 mm was caused by the lens. This was believed to be due probably to lack of perfect centering of the lens elements, which is critical with respect to the distortion properties. The second 4.402-in. lens was not tested.

Since only a central strip of each rectified photograph was used in the mapping test the distortion was not troublesome. The distortion tolerance could well be relaxed for mapping under such conditions, but not when the entire area of the photograph is to be used.

MANUFACTURING PROBLEM

Two simple lenses for rectification were made and delivered to the Hydrographic Office. Their focal lengths were 2.40 in., and their apertures

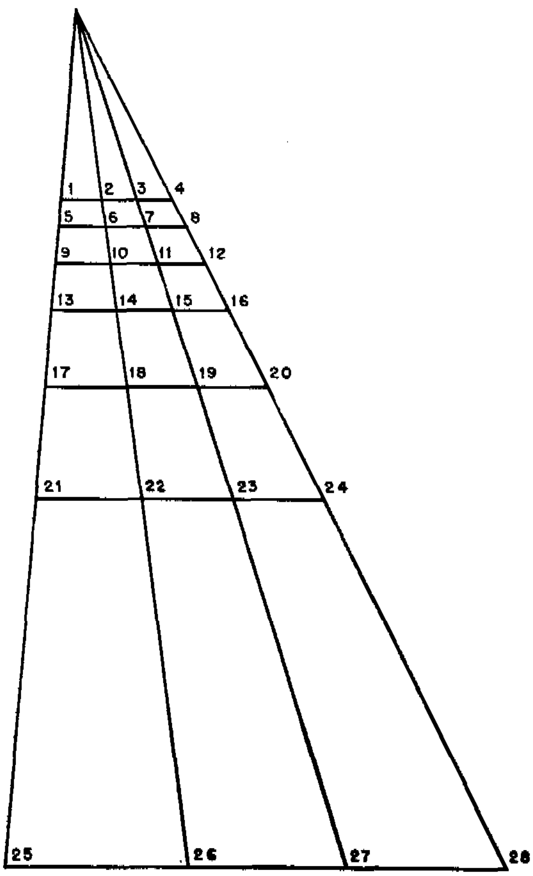

FIGURE 4. Target locations for resolution tests.

0.015 and 0.030 in. These lenses presented no manufacturing problems.

Four Hypergons were made: one with focal length 3.464 in., used for the tests and later delivered to the Engineer Board, Fort Belvoir, Va.; one with focal length 1.484 in. delivered to MFA for their one-stage rectifier; two with focal length 4.402 in., delivered to MFA for use in their two-stage rectifier.

These lenses were somewhat difficult to manufacture. The edge thickness is only 0.013 in. in the 3.464-in. lens. Consequently it was necessary to support the edge throughout all operations. This was done by first grinding and finishing the concave internal curves of both elements, lapping the ring surrounding the concave face, edging the disks centered, and grinding the back side parallel to the lapped ring as measured by a 0.0001-in. dial gauge.

A blocking tool was then made consisting of two identical glass hemispheres ground to fit the finished concave surfaces and of precise thickness. The two elements and the two hemispheres were then blocked with balsam to form a solid cylinder, and the blocked assembly ground and polished to a perfect sphere of appropriate diameter.

It was found that silicon carbide leaves subsurface bruises which weaken the thin edges, so that several lenses cracked. In the later work the last 0.005 in. was removed with No. 302 emery.

The first Hypergons were cemented into their cells, without retainer rings, because of the steepness of the curves. The second 4.402-in. Hypergon was mounted with retaining rings in a cell of special design, which included an aperture whose plane was inclined 60 degrees to the axis of the lens, and a similarly inclined barrel or hood. The hood and the walls of the aperture were threaded to reduce flare.

3.3.7 MFA Method for Mapping from High Oblique Photographs

Upon their return from Hawaii in June 1944, the field party recommended the immediate development of a method for mapping at large scales from high oblique photographs. The value of oblique photographs as opposed to vertical photographs can be argued at length. The advantages of the large area included in each oblique photograph, with consequent reduction in the amount of flying and ground control required, are offset by the great variations in scale and resolution in different portions of the photographs and the obscuration which occurs frequently because of the angle of view.

For commercial and peacetime operations no valid general decision can be made because of lack of experience with oblique photographs. For military operations the reduction in flying and ground control assumes great importance, and the value of having available a method for using oblique photographs becomes apparent. However, more important as a reason for developing such a method than any theoretical considerations was the fact that a great many high oblique photographs had been taken and were already available, and more would be taken in the trimetrogen photography with which the Army Air Forces had covered a large part of the Pacific area. These photographs in many cases included areas not otherwise covered, and the cost in lives, time, and equipment of covering those areas with vertical photographs was not warranted if the oblique photographs could be used.

The question of the most suitable method was considered from fundamentals with the object of developing a method which would lend itself to production in large quantities, without large numbers of highly trained specialists and with the greatest possible accuracy. The arguments which led to photographic rectification in the problem of delineation from oblique photographs (see Section 3.3.5) led also to rectification here. The practical problems in using rectified images, for which the datum scale and contour interval are constant in the area of the image, are much easier than when the oblique photographs themselves or intermediate partial rectifications are used. The theoretical accuracy also is greater with rectified photographs if an optimum plotting procedure is used. Between photographic rectification and projection of a rectified image, as by the multiplex, the former was chosen because of its better image quality and easier operation. Plotting directly in orthographic projection was chosen as leading to simpler instruments. For control, the existing radial line method using the rectified photographs appeared quite satisfactory without fundamental change.

Description of the Method

No mapping method consists of a specific set of procedures which is applied unchanged to every job. The instruments and procedures which constitute a method are actually rather general techniques for performing the various operations necessary to mapping, and their specific application may be varied from time to time to meet changing conditions. To describe a method, therefore, it is necessary to describe it with respect to some application, but it is obviously valueless to select a concrete example so that procedures may be described explicitly, since the same conditions may never arise again.

In the following description of the MFA method the application in mind is topographic mapping, at whatever scale may prove feasible from the wing pictures of trimetrogon photography, of an area containing suitably located elevation control. In mapping from such photography the vertical photograph also would be used. But this method is concerned only with oblique photographs; the verticals would be treated according to any of the existing vertical methods. The operations are:

1. *Photography.* Strips of 60-degree oblique photographs, taken with a 6-in. camera on 9x9-in. film. The principal planes are parallel, and are perpendicular to the line of flight. Spacing of exposures along the line of flight is the same as the spacing for verticals with 55 to 60 per cent overlap, but flight lines are spaced three to four times the flight altitude.

2. *Preparation.* The negatives are processed and indexed by standard procedures.

3. *Rectification.* Photographs are rectified according to one of the procedures described later in this section. Two rectified photographs are produced: one consisting of several prints of different parts of the photograph, for plotting; the other consisting of one large paper print, for control.

4. *Control.* Minor control points are located by a radial control plot, using any one of the standard methods for radial control, and using rectified photographs. The details of procedure are affected by two characteristics of oblique photographs:

   a. The nadir point is not in the image area of the photograph. It must be located by using the accompanying vertical photograph, or by trigonometric com-

putation if there is no vertical photograph.

b. The nadir points of photographs in the adjacent strip appear, and should be used. Such cross-strip azimuth lines strengthen the plot.

5. *Plotting.* Because of the great relief displacement in oblique photographs, both planimetry and contours are plotted in succeeding operations in the plotter developed for the purpose. This and its use are described in this section.

6. *Preparation of the Manuscript.* The plots from the several pairs of photographs are all at slightly different scales. They are brought to the scale of the control plot and compiled according to standard procedures.

The rectification and plotting techniques which were developed to utilize high oblique photographs are radically novel. The other operations may all be performed using standard techniques, and there is no need to discuss them further here. The techniques for rectification and plotting, and some of the theory, are described below.

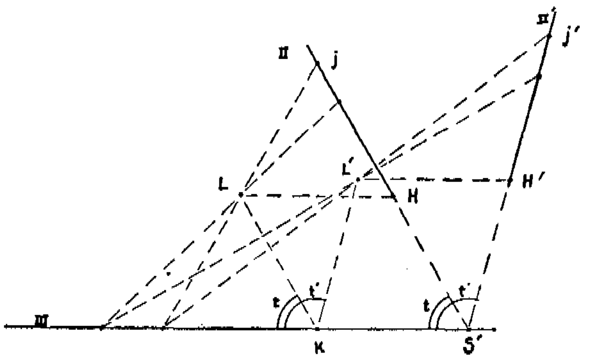

FIGURE 5. Change of tilt angle in rectification.

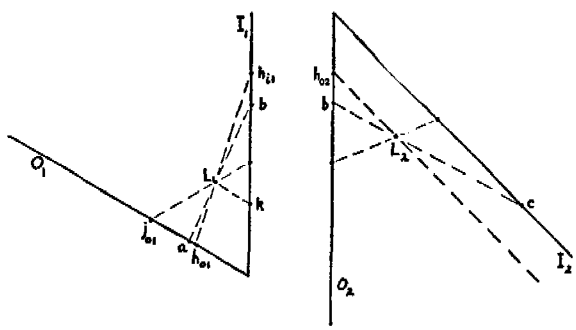

FIGURE 6. Illustrative two-stage rectification.

RECTIFICATION OF HIGH OBLIQUE PHOTOGRAPH

Principles of Rectification. The most elementary principle of rectification is illustrated in Figure 1, by the projection of plane II through L onto plane III. The negative is projected through a perspective point onto a horizontal plane with all parts in the same relative positions as at the time of exposure.

This arrangement was used in the pinhole cameras but is never used when a lens serves for projection. Since plane III is not at an infinite distance, the focal length required of the lens changes with change in tilt, and this is impractical. It was mentioned in Section 3.3.1 that a perspection is not uniquely determined by a given object and image, but that one degree of freedom remains. This is represented in Figure 5.

Plane II, L, and plane III are here in the same positions as in Figure 1. If plane II is rotated about S' to any other position, and L is rotated about K through the same angle to L', then the projection of II′ through L' on III gives identically the same image on III as the projection of II through L on III. It is easily seen that j, H, and S' remain in the same relative positions on II′ as on II, and according to one of the properties stated in Section 3.3.1 this is sufficient to assure that the perspections are the same.

In order that II or II′ focus on III with a lens at L or L', in the position drawn in Figure 5, the axis of the lens must lie on Lj or $L'j'$. It is obvious that the focal length required changes with change in t, even though the perspection is the same.

In practice this property is used inversely, so that a fixed focal length may be used for different perspections by using in the rectification an angle t' different from the angle t representing the tilt at which the photograph was taken. Rectifying cameras are built with freedom to change the angle between the object and image planes, and for any particular photograph the camera is adjusted so that

$$F \csc T = f \csc t,$$

[redacted]

where F is the perpendicular distance from the lens to the object plane in the rectifier, T is the angle between object and image planes of the rectifier, f is the principal distance of the aerial photograph, and t is the tilt of the aerial photograph. In fact, in practical design this property is used still more intensively, so that the angle T seldom even approximates t. In order that good process lenses of long focal length and narrow field may be used, most rectifying cameras are designed with F and T several times larger than f and t.

The negative is placed on the object plane of the rectifier so that its isocenter and horizon coincide with the isocenter and horizon of the rectifier, and the desired perspection is thereby achieved. The isocenter of the rectifier is a point on its object plane having with respect to the image plane the same angle-preserving property as j in Figure 1. The horizon of the rectifier is a line on its object plane having with respect to the image plane the same property as H in Figure 1, namely, that there is no image of H on plane I (or plane III).

This presentation of the principles of rectification is different from that usually given. Ordinarily the subject is treated trigonometrically, with reference to obtaining the correct distance between points on the rectified image. Although not detailed, the treatment here has been with respect to the angle-preserving property of the isocenter and the lack of image (or zero scale) at the horizon. While this theory is obvious once it has been stated, the theoretical contributions to the theory of rectification came from explicit recognition of the following simple facts.

1. On the object plane of a rectifier there exist a point and two lines having special properties with respect to the image plane, namely,

an isocenter	(conformality),
a horizon	(scale $= 0$),
an isoline	(scale $= 1$).

2. On an oblique aerial photograph there exist similar quantities having the same properties with respect to the datum plane (but reduced in size) or to the desired rectified photograph. A necessary and sufficient condition for obtaining a rectified image at a desired scale is that the isocenter, horizon, and isoline of the photograph be placed in coincidence with the corresponding quantities on the object plane of the rectifier.

3. The process for rectification is quite immaterial, and may use any means so long as it provides an object plane and image plane, makes a straight line in the object plane appear as a straight line in the image plane, and provides on the object plane an isocenter and horizon. The existence of an isoline is implied by the other conditions.

The practical importance of these facts lies in item (3). If a process can be devised having a sufficient amount of freedom in the steps between the object and image planes, then by proper use of this freedom it might be possible to reduce distortion. Ordinary rectification has only one degree of freedom, and this is used to permit a fixed focal length. Multiple-stage rectification has an unlimited number of degrees of freedom, and it turns out that these may be used to reduce distortion.

Multiple-Stage Rectification. The process which was devised has been called *multiple-stage rectification,* since in it an oblique photograph is subjected to several photographic projections in succession. The image in one step is used as the object in the next step, and the final image is a rectified photograph. The object and image planes in the projections may be either parallel, as in a ratio camera, or inclined, as in a tilt camera. A simple example of this is illustrated in Figure 6 showing two successive tilt projections.

An object (photograph or negative) is placed on O_1 and photographed on I_1. This image is developed, placed on O_2 (the relative positioning between I_1 and O_2 must be specified as part of the process), and photographed on I_2. A point at a on O_1 appears eventually at c on I_2.

Except in a certain special case, there always exist a point and a line on the first object plane having the properties of isocenter and horizon with respect to the last image plane. In Figure 6, for example, by starting with a line through L_2 parallel to I_2, and tracing backward, the line h_{o1} is found. This line obviously has no image on I_2. Only if, in transferring h_{o2} to I_1, h_{i1} were to fall at the point k on I_1 would there be no

line h_{01} on O_1. This occurrence gives rise to the special case and in this case the transformation between the first object plane and the last image plane is an *affine* projection, rather than a general perspection.

If a horizon exists on O_1, then a unique isocenter also exists. This is more difficult to show than is the existence of a horizon, and will not be attempted in this summary report. Its existence is shown in the literature.[4, 5] In Figure 6, j_{01} is the isocenter. While not a conformal point for either perspection separately, it is conformal for the combination. The lack of conformality in each of the two steps cancel. Since this process provides object and image planes, and a horizon and isocenter on the object plane, it is a rectification process.

Applications. Several advantageous applications of these principles were worked out. In these applications it would have been possible to permit the inclination of object and image planes in the several instruments to be varied, thereby varying the distance from isocenter to horizon in order to accommodate photographs with different tilts, as is done in single-stage rectification. For practical reasons, however, it was decided to build the tilt cameras with fixed angles, and to vary the isocenter-to-horizon distances of the photographs themselves by enlargement or reduction before rectification. This is really a further application of the principles already stated, and the entire process may be considered a multiple-stage rectification process, in which the first step is a variable ratio printing. By this process the rectified photographs would all come out at different scales, and hence an additional variable ratio printing must be added as a last step.

1. *One tilt projection.* The distortion characteristics and field of the rectifying Hypergon lens were so good that it could be employed in a rectifying camera of standard type for 6-in., 60-degree oblique photographs. Limitations would be imposed on the scale ratio during rectification; in particular, the field, even of the Hypergon, was not great enough to permit a sizable reduction during rectification. The rectified image of the useful portion of a high oblique photograph, if not reduced in scale, measures about 30x40 in., which is too big to reduce conveniently photographically. Since freedom to vary the scale was essential, the standard type of rectification was not pursued in this project, but was applied in a slightly different fashion requiring three photographic steps, only one of which is a tilt projection. The steps are:

- a. Reduction of normally about 3×, but variable to adapt the perspective index of the reduced print to that of the rectifying camera.
- b. Rectification at 1/1 scale in a single stage, in a fixed rectifying camera designed for photographs of 60-degree tilt and 2-in. principal distance.
- c. Enlargement or further reduction of the rectified photograph to desired scale.

This process requires a variable ratio camera adaptable to double use, or two such cameras, and a single-stage fixed rectifier designed for 1/1 rectification of reduced high oblique photographs. In both this process and process (2) below the variation in tilt of the aerial photographs to be processed is taken care of by varying the initial reduction or enlargement rather than by varying the angle of the tilt camera. These instruments were constructed and are described later.

2. *Two tilt projections.* This application contemplates five photographic steps, which are:

- a. Ratio printing at normal 1/1 ratio, but variable to adapt the perspective index of the print to that of the rectifying camera.
- b. and c. Rectification in two stages of tilt projection, both of them identical and performed by two successive projections in the same fixed-angle tilt camera. During the rectification a reduction of 3× is imposed.
- d. Contact print, for reversal.
- e. Enlargement or further reduction of the rectified print to desired scale.

While more steps are required in this process, it is preferred to process (1) for several reasons. The conditions under which the reduction is imposed are better for preserving image quality. The lens is larger, and in general tolerances are less critical. Light enters the image

[redacted]

plane much less obliquely, thereby increasing the illumination and reducing the effect of non-uniformity over the image surface.

The process requires a variable ratio camera as in process (1), and a two-stage, fixed-angle rectifying camera designed for rectifying 6-in., 60-degree oblique photographs, with 3× reduction during rectification. These instruments were constructed and are described later.

3. *Three tilt projections.* For achieving accurate rectification in practice the preceding methods have two faults. First, identification and measurement of points for determining tilt must be done on the oblique photographs. As remarked in Section 3.3.4, this operation is less accurate than identification on vertical or rectified photographs. Second, several steps intervene between the determination of tilt and the ultimate rectified photograph. Accidental errors occurring in the intervening steps will accumulate in the rectified photograph.

The following procedure was therefore devised to permit determination of tilt on a nearly rectified photograph immediately preceding the final step. Three photographic steps are required:

a. and b. Approximate rectification of the high oblique photograph, using a rough tilt determined from the horizon. This is done in two stages on the two-stage rectifying camera of process (2). The perspection is so chosen that little tilt remains in the approximately rectified photograph, and the isocenter of this photograph with respect to the datum plane has been moved from near one edge to the center of the image area. This permits the photograph to be treated further in a rectifier of the type ordinarily used with near-vertical photographs. Accurate residual tilt is determined by identification and measurement on this photograph.

c. Final rectification and enlargement or reduction to desired scale simultaneously on a variable-angle, small tilt rectifier of standard design.

This application requires a near-vertical rectifier of standard design and a two-stage fixed-angle rectifier similar to that required in process (2) but designed to use aerial roll film in the first stage. A variable ratio printer is not used. These instruments were not made, but the method was tested experimentally at Aero Service, using the existing two-stage rectifier and a Brock rectifier and Brock enlarger.

INSTRUMENTS

The following instruments, necessary for testing and demonstrating the methods of rectification described above, were constructed:

Variable Ratio Printer. This camera, for use in the first and last steps of methods (1) and (2) above, was designed and constructed by Aero Service Corporation. It is illustrated in Figures 7 and 8.

Item *A* is the light box, containing four 100-w high-pressure air-cooled mercury-vapor arc lights diffused by opal glass. For the first step in each method the object is an aerial negative. The roll of film negatives passes from one spool to the other, and is held, one frame at a time, between pressure plates in the object plane *B*. The image for method (2) is received on a 14x17-in. glass plate *C*. For method (1) the glass plate at *C* is replaced by an adapter carrying a lantern slide plate. This adapter was not constructed. Means are provided for positioning all parts accurately.

For the last step in each method, the object is a portion of a 14x17-in. glass plate carrying the rectified image. It is inserted in the slot *D*, and may be positioned so that any small portion lies in the field of the lens. The image is received on paper held between two glass plates at *C*.

One-Stage Fixed Rectifier. This camera, for use in method (1), was designed by MFA and constructed in the shop of the Mount Wilson Observatory. It is illustrated in Figures 9 and 10.

Item *A* is the light box, containing one 250-w medium-pressure air-cooled mercury-vapor arc light, which is condensed on the lens by an elliptical reflector. The object is a lantern slide at *B*. The image is received on a 14x17-in. glass plate resting on the eight pads *C*, and clamped there by opposing pads on the cover *D*. The Hypergon lens, 1.484-in. focal length, $f/30$, is seen at *E*.

The object is positioned automatically by three stops against which the edges of the object plate rest. These stops are duplicated on the image plane of the variable ratio printer, where all positioning of the image is done.

The perspective index of this camera is 2.297 in. The preliminary reduction must be such as to reduce the perspective index of the aerial photograph to this value.

[redacted]

Two-Stage Fixed Rectifier. This camera, for use in method (2) was designed by MFA and constructed in the shop of the Princeton University Physics Department. It is illustrated in Figures 11 and 12.

Item *A* is the light box, containing two 250-w medium-pressure air-cooled mercury-vapor arc lights diffused by opal glass. The object is a 14x17-in. glass plate at *B*, clamped against eight pads lapped to a plane. The image is received on another 14x17-in. glass plate held similarly at *C*. The Hypergon lens, 4.402-in. focal length, may be seen at *D*.

The position of the object for both the first and second stages is determined by three stops against which the edges of the plate rest. These stops are duplicated on the image plane of the variable ratio printer, where initial positioning of the image on the glass plate takes place, and serve to carry this position over to the object plane of the rectifier. The stops are also duplicated on the image plane of the rectifier, thereby carrying position from the first to the second stage of rectification. The latter set of stops may be seen at *E*.

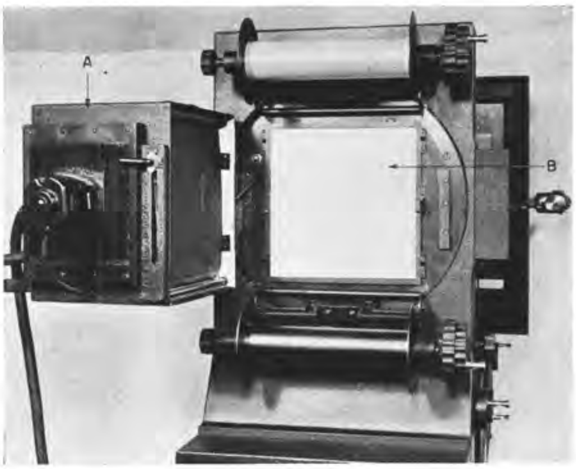

FIGURE 7. Variable ratio printer—object end.

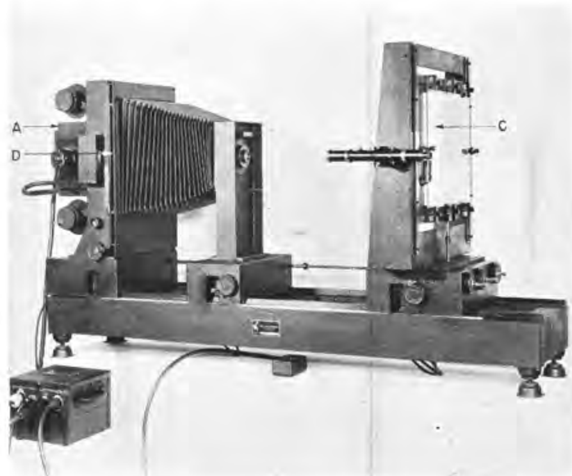

FIGURE 8. Variable ratio printer—side view.

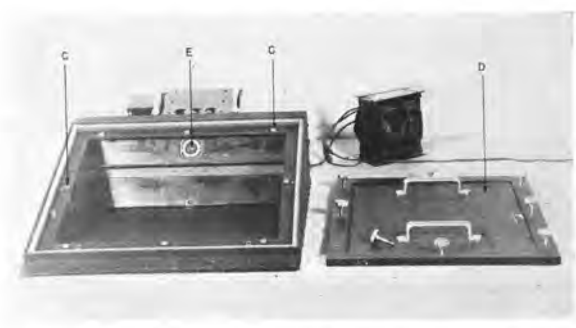

FIGURE 9. One-stage fixed rectifier—image end.

FIGURE 10. One-stage fixed rectifier—side view.

The perspective index of this camera is 7.072 in. The preliminary enlargement or reduction necessary for the use of this camera in rectification method (2) must be such as to bring the perspective index of the aerial photograph to this value. As an illustrative example, the scale changes necessary for photographs whose principal distance *(f)* is 6 in. are tabulated below for several different tilts.

Tilt t	Perspective Index $Q = f \csc t$	Enlargement $E = 7.072/Q$
55°	7.325	0.96550
57°	7.154	0.98850
58°2′22″	7.072	1.00000
60°	6.928	1.02075
62°	6.796	1.04075

[redacted]

Orthographic Plotting from Rectified Oblique Photographs

Principle. The principle of stereoscopic plotting has been described in Section 3.3.2. If the photographs are rectified and are both at the same scale, the plotting instrument becomes much simpler. In addition, the photographs need not be viewed from their perspective centers. They may be viewed from any points perpendicularly over the nadir points, the same distance above each photograph, and this will only change the vertical scale of the floating mark's motion.

FIGURE 11. Two-stage fixed rectifier—image end.

For rectified high oblique photographs, existing plotters giving orthographic projection were unsatisfactory because of the requirement that the points of view be over the nadir points of the photographs. Viewing from this position would lose a considerable part of the value of rectification, since the angle subtended at the perspective center of points on a photograph is not changed by rectification. The apparent scale in the background would then be very much smaller than in the foreground, with resultant loss of accuracy in plotting. It is desired to view the photographs from points as nearly as possible over the points being plotted, or over the center of the area of the image being plotted, in order to obtain uniform apparent scale in viewing all parts of the rectified photographs.

It was found by analysis that the projection is orthographic if:

1. The pair of rectified photographs is oriented for plotting as if they were to be viewed from the perspective centers (see L, Figure 13).
2. The points of view are then moved parallel, while maintaining the same separation, to any new positions (see L', Figure 13) vertically over points m on the photographs.
3. A plotting principle is used, similar to that for orthographic projection, but in which the horizontal position of the stylus is unchanged when the reticles move in the direction $L'n$, rather than when they move vertically.

For an experimental model of such a plotter an equivalent principle was used, namely, the stylus was moved horizontally as the reticle marks were raised vertically to pass from one contour to another.

Orthographic Plotter for Rectified Oblique Photographs. An experimental plotter employing the principle described in the preceding paragraphs was designed by MFA and constructed by Chicago Aerial Surveys. It is illustrated in Figures 14 and 15.

FIGURE 12. Two-stage fixed rectifier—side view.

Item A is a mirror stereoscope with two "photographs" in position below it. The reticle marks B may be moved vertically on posts C. The stylus is at D and may be moved radially on the track shown. The direction of the track may be changed. Item E is a parallel motion device, operating on the usual parallelogram principle, to permit only parallel motion of the pair of reticle marks horizontally.

Complete adjustments are provided for setting the reticle marks parallel to a line joining the perspective

[redacted]

centers, for changing their separation with different pairs of photographs, and for accommodating differences in operators' interocular distances.

Partial Test of the Proposed Method

Since many of the operations outlined in the brief description of the proposed mapping method given earlier in this section are to be accomplished by standard procedures, it was not necessary, nor was it feasible with the limited equipment available, to demonstrate the complete method during the experimental phase of the development. The novel procedures, consisting of the rectification and plotting steps, were tested on a single pair of photographs, selected from those taken for the studies of photographic quality (see Section 3.3.3). They were taken with a K-17 camera, 6-in. Metrogon lens, on infrared film at 65-degree tilt and 5,000 ft altitude. They are remarkably clear in the background. The terrain is rugged, cut by many almost vertical canyons.

The photographs were rectified by a modification of rectification process (3). Since the two-stage rectifier did not accommodate film negatives, contact prints of the negatives on 14x17-in. glass plates had first to be made. These were rectified approximately on the two-stage rectifier. Since an appropriate instrument was not available for the last step, the final rectification was done on the Brock equipment at Aero Service Corporation. The Brock rectifiers project only at 1/1, and hence the required scale change was imposed in the Brock enlarging camera. Thus, five photographic steps were used instead of the three proposed, but the photographic quality was still good.

The rectified prints were contoured in the experimental orthographic plotter and compared with an existing map of the region by means of profiles. Substantial agreement was found to within the usual mapping tolerance of 0.02 in. in horizontal position and one-half contour in elevation. No systematic differences appeared, and hence the theory of the method was substantiated. Quantitative measurements of local accuracy could not be derived, but it was found in contouring that differences in elevation could be readily distinguished to permit mapping with a contour interval $1/500$ of the flight altitude. This is in the region of lower accuracy when compared with mapping from vertical photographs, which permit contouring at $1/800$ to $1/500$ of the flight altitude, depending on the method used, but is good for the first run of a new method with high oblique photographs.

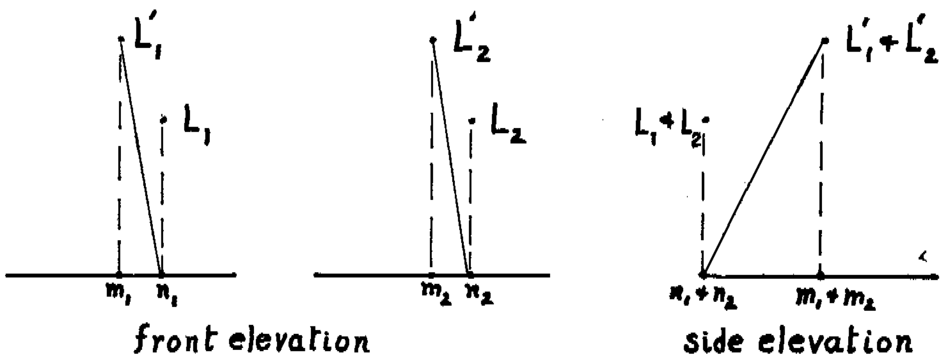

FIGURE 13. Change of viewpoint for plotting rectified obliques.

Since the rectification process is practically free of distortion, horizontal accuracy can be maintained, certainly at the negative scale and possibly at larger scales, depending on the portion of the negative used for mapping.

Plans were laid for an intensive test of the complete method, in cooperation with the Hydrographic Office and other government mapping agencies. NDRC was to complete the development of the instruments, adapting the two-stage rectifier for roll film and producing an improved plotter. The Hydrographic Office was to provide space and additional equipment, and all cooperating mapping agencies would loan personnel. This plan was dropped at the end of the war and the termination of NDRC contracts. The Office of Research and Inven-

[redacted]

tions, Navy Department, has indicated a desire to take over the development and continue the original plan.

3.3.8 Two-Camera Method for Water Depth Determination

One problem of great importance in the preparations for amphibious assault operations was the accurate determination of inshore water depths by means other than soundings. In the spring of 1944 this problem was in the early stages of solution. Many methods had been proposed, including color analysis of the water, coral analysis, wave formation, and several photogrammetric methods. The contractors under Project NA-124 were requested to give whatever assistance they could to these developments.

All of the photogrammetric methods depended on photographing the bottom of the water from two or more positions and determining the elevation of the bottom by the usual stereoscopic procedures or computational or graphical equivalents. The most practical method employed stereoscopic depth measurements on strip photographs taken with the Sonné stereostrip camera at altitudes of 100 to 500 ft, the surface of the water being used as a plane of reference.

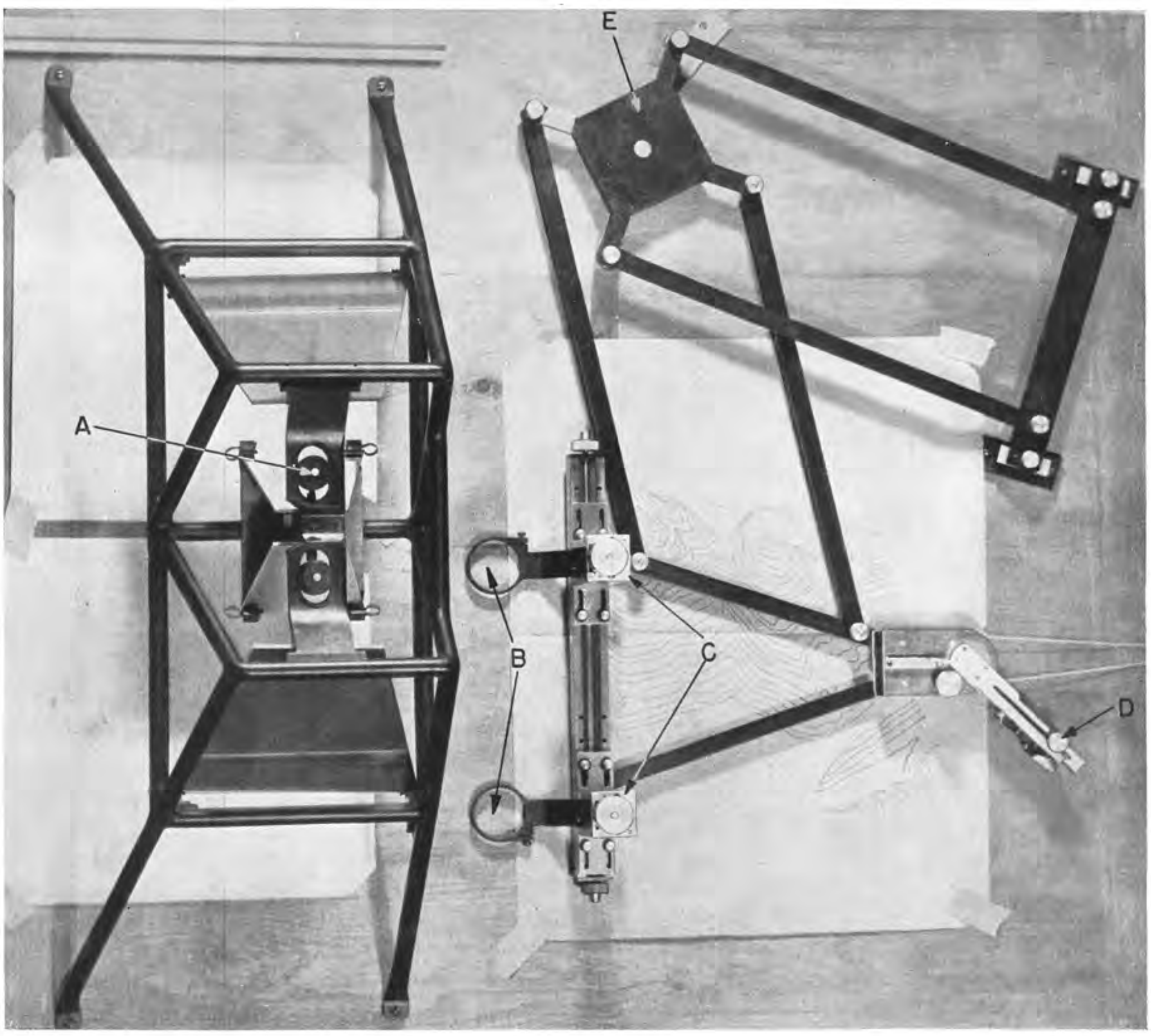

FIGURE 14. Plotter—top view.

[redacted]

This method was under development by the Photographic Interpretation Center.

The stereostrip camera is essentially a double-strip camera so arranged that one chamber photographs the ground slightly ahead of the airplane and the other chamber slightly behind the airplane. On such photographs, taken from low altitude and exposed almost simultaneously, both the surface and the bottom of clear water can be seen stereoscopically, the wave reflections and shadows forming patterns excellent for stereoscopic fusion. The two strips viewed simultaneously give a stereo-

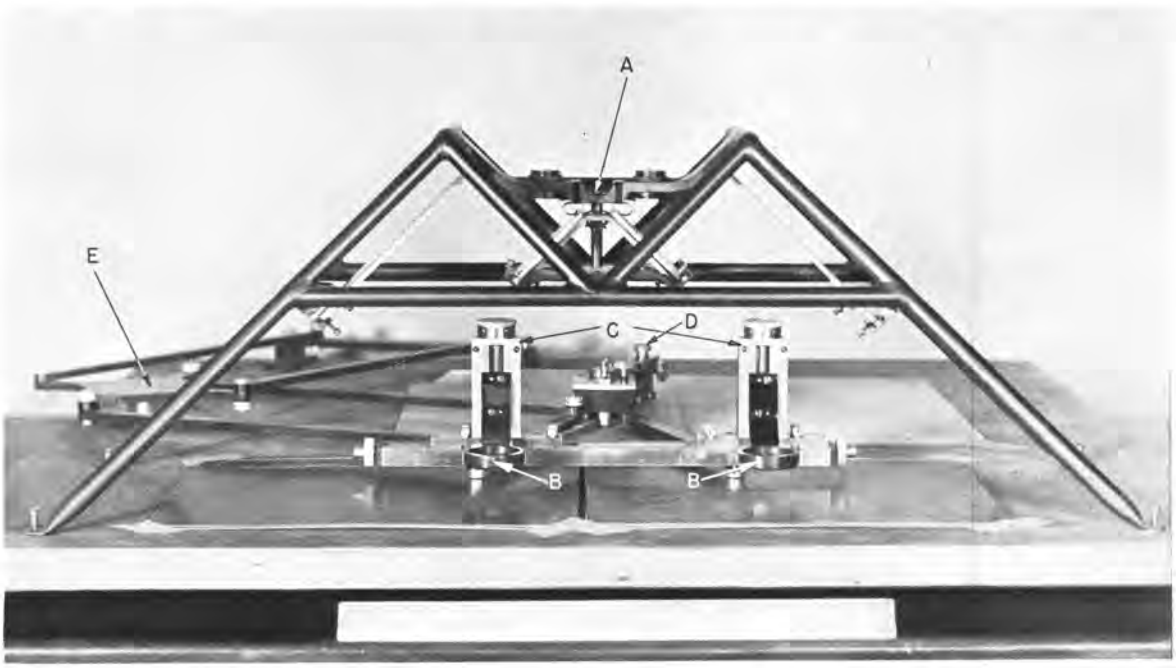

FIGURE 15. Plotter—front view.

scopic model for which the airbase (line joining the two viewpoints for any particular image) is in the line of flight of the airplane.

Difficulty in computing depth arises because the length of the airbase and the relative orientation of the two views change continually with changes in altitude and pitch of the airplane. Errors in film-speed setting due to ignorance of true altitude and ground speed also lead to unknown errors in the depth determination. To overcome these difficulties MFA proposed that two single-strip cameras be mounted in the wings of an airplane, thereby fixing the airbase and relative orientation. A preliminary study was made to determine whether the cameras could be mounted in the wings of a F-6-F. A method of calibrating the installation and computing depth from the stereoscopic measurements was devised, and the errors to be expected, chiefly from bending of the wings, were analyzed theoretically. This material was turned over to the Photographic Interpretation Center, with a recommendation that a trial installation be made to determine the amount of wing bending to be expected and to discover any other source of error.

The suggestion was well received, and preparations were made by the Photographic Interpretation Center for a trial of the wing installation. However, by this time (the end of August 1944) the stereostrip camera method had been tested and found to work satisfactorily in trial runs. A party was soon to be sent out to the Pacific to apply the method, and it was considered desirable to await reports on their success before giving high priority to a new development.

Preparations for the installation of wing cameras proceeded slowly, with low priority,

throughout the year. At the end of January 1945, drawings and a mockup had been completed, and the final installation was ready to be made. This installation was delayed by work of higher priority, and was suspended indefinitely at the end of World War II.

3.4 RECOMMENDATIONS BY NDRC

It is not easy to foresee what map information will be required by the Services in the future. However, it seems clear that it will be desirable for the Army and Navy to have available as wide coverage as possible at a scale of 1/20,000, with means ready at hand for producing maps and charts at larger scales of selected regions for special purposes.

3.4.1 General Recommendations

1. Both the Army and Navy should maintain mapping organizations with well-trained personnel during peacetime. In addition, at least part of the mapping work should be subcontracted to civilian agencies (both government and private) to maintain the organization and working relations which would prove invaluable if these agencies should be called upon to map for the Services in another emergency.

2. The Navy should establish and maintain small, fully equipped mobile units, specifically for mapping, and should keep them well trained.

3. Cartography should be completely separated from photographic reconnaissance. Any duplication in photography will be more than counterbalanced by the saving achieved in using photographs taken specifically for mapping. *Mapping pilots and photographers should be selected and specifically trained for that task,* and that should be their primary occupation.

4. The Federal Government should participate in the technical developments relating to mapping, and should provide financial support for private development. The situation is different from that in other industries where large production permits private concerns to set aside adequate funds for research. The major part of the map production and related activities in the United States is carried on by the Federal and State Governments, with *no* provision for technical development. All development to date has arisen:

   a. In Government bureaus, incidentally, in the course of production, without special planning or provision for this part of the work. This is notably inefficient and not very effective.
   b. In private concerns which, because of their small share in production, cannot devote sufficient funds to carry on the development needed.
   c. In universities, by men not well acquainted with or directed to practical production problems.
   d. By the Federal Government, during World War II (but not now), through the NDRC.

These sources of development work are quite insufficient to provide the advancement in theory and technique that are now needed and possible in photogrammetry. This is particularly true at this time when progress has been made in so many other fields, such as radar, which should be applied to mapping, but whose further development for such a special use will undoubtedly be expensive.

3.4.2 Technical Recommendations

1. The developments mentioned in Section 3.2.3 should be prosecuted. These are: aerial triangulation, photogrammetric sounding, and wide-field photogrammetry. Aerial triangulation may prove particularly applicable to the problems concerned with guided missiles.

2. Mapping photographs should be treated as engineering data, not merely as pictures. Precision equipment, materials, and processes should be used throughout. Attention should be given to precision cameras and photographic materials, to special purpose emulsions, and to processing techniques for maintaining accuracy.

3. Carefully planned production tests should be conducted on the Merrill Flood and Associates method for mapping from high obliques

when all necessary equipment has been made available. Such a test should make it possible to evaluate the usefulness of the process, in comparison with mapping from verticals, for various applications.

4. The two-camera method of determining underwater depths should be tested by completing the installation in the wings of the F-6-F which has already been undertaken or by making a similar installation in another airplane.

5. Lenses of the highest possible quality should be used in all mapping operations. The many factors discussed in Chapters 1 and 2 which affect resolution of photographs should be given full consideration in selecting equipment for mapping.

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Chapter 4

OPTICAL TESTING METHODS

By *Roderic M. Scott*[a]

4.1 INTRODUCTION

At the request of the Frankford Arsenal, NDRC undertook a study of optical testing methods in 1943, under Project OD-138. The request was primarily for a survey and evaluation of the methods of optical inspection which were employed at that time. Under Contract OEMsr-1197, members of the Department of Physics of the Pennsylvania State College[1] were to prepare a report describing inspection methods, assessing them, and recommending any changes considered to be desirable by the surveying group. The development of new equipment and methods of inspection was to be a second, but equally important, part of the undertaking. Both government agencies and private contractors engaged in the manufacture of optical components and instruments were included in the survey. The requested survey has been made[2] and has shown that many of the current methods of optical inspection are to a large degree dependent on the subjective reactions of the inspector. It was therefore one of the primary recommendations of the survey group that new methods be developed which would be, as far as possible, impersonal and which would yield quantitative results upon which the quality of the optics under inspection could be assessed. As a result of this recommendation, several new inspection instruments are now employed which reduce the effect of personal judgment to a minimum.

One of the most important developments designed to aid in optical inspection is that of a device which measures the angular resolution of a telescopic system. This device is now extensively employed to control the production of optical instruments for military purposes. It is known as the *kinetic definition chart* [KDC] *apparatus*.[3] The apparatus was an outgrowth of the work of Fabry.[4] A test object made up of a number of parallel black lines is viewed first with the unaided eye or through a telescope, and then with the eye or the same telescope plus the instrument being inspected. The test object is moved toward or away from the observer until the parallel lines are just resolved. The distance to the object viewed with the test telescope should be equal to the magnification of the telescope times the distance to the test object viewed without the telescope. The percentage ratio of the observed distance to the theoretical distance is called the KDC efficiency. It was established that the efficiency was nearly independent of the auxiliary magnification over a wide range. The results given by this instrument appear to be almost completely impersonal.

It seemed possible that the resolving power of the eye might affect the results of an apparatus such as the KDC machine. In view of the intimate connection between the optical properties of the eye and instruments which it is used to inspect, a study was made of the resolving power of the eye as a function of pupil size. Further carefully controlled measures should be made.

The Michelson-Twyman interferometer has undergone considerable development[5] and study to determine its usefulness as an inspection instrument. The observed field in the interferometer consists of an array of dark bands whose number and shape are related to the optical performance of the lens, prism, or instrument under observation. Methods for computing the form of the interference pattern for a perfect example of the device or component under test have been described in the literature. Although the interferometer was very little used before World War II, many optical manufacturers now find that it is a great aid for inspection purposes.

Another device developed at Penn State is an apparatus for the study of distribution of light[6] in the image formed by an optical system. Its usefulness in the evaluation of an optical design

[a] The Sharples Corporation.

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is second only to direct ray tracing whether by computation or by the Hartmann method. The technique was originally developed by the Eastman Kodak Company for the evaluation of camera lenses and has been extended to general optical instruments. Both a photographic method and a recording photoelectric method have been used.

Two small but useful inspection devices developed by the group are the *dioptometer*[7] and the *proboscope*. The dioptometer is a small telescope with adjustable spacing between the objective and an eyepiece equipped with a reticle. It is used to measure the degree of divergence or convergence of light at some point in an optical system. It is very useful for measuring spherical aberration and the parallelism in sighting telescopes. The proboscope consists of a group of supplementary lenses which, when slipped over the end of a telescope or other optical system, bring to sharp focus the surfaces of each interior optical component in turn. This device makes easy inspection of individual lenses and prisms for surface defects and cleanliness without requiring the disassembly of the instrument.

As an adjunct to the KDC equipment, an *artificial sky apparatus* was developed to permit the study of the effect of scattered light upon the resolving power of optical instruments.[8] In addition, measures of scattered light may provide a means for determining the conformity to specifications of striated glass. The combination of KDC apparatus, artificial sky apparatus, and a holder for the pieces of glass under test has been called the *striaescope*.

4.2 SURVEY OF PRE-WAR AND CURRENT OPTICAL INSPECTION METHODS

The primary task of the Pennsylvania State College group was to examine, evaluate, and report upon the methods of inspection of optical devices and components which were used in 1944 to 45. The survey covered methods used both in production plants operated by the government and by a large number of contractors for the production of military optics. The study included the specifications controlling the production of optical glass, components and finished instruments, as well as the effectiveness of inspection methods which are used to ascertain the degree of compliance with the specifications.

It is the purpose of the specifications to fix a level of quality that an instrument must possess in order to permit an observer to receive the benefit of all the performance inherent in the design. The specifications must be sufficiently rigid to insure this, but they must not be more rigid than is required. If they are placed higher than necessary, production is slowed and many useful parts are discarded. Specifically, the specifications should not ordinarily include requirements intended merely to improve the appearance of an instrument if they do not also improve the performance.

In conducting the survey, each specification was examined in detail and each inspection method and inspection device was studied under production conditions. It was hoped that the survey would produce material for an inspection manual covering satisfactory specifications and methods as well as new and improved specifications and instruments.

4.2.1 Optical Glass

INDEX AND DISPERSION

The joint Army-Navy Specification JAN-G 174 sets forth the specifications and tolerances on the optical constants of glass used for military optical purposes. For such purposes glass is procured in three physical forms: slabs, molded blanks, and chunks. Very little use of chunk glass was encountered. Table 1 sets forth the indices, partial dispersions, and tolerances for the types of glass procured by the Government. In addition to physical constants, the specifications on optical glass prescribed definite sampling techniques. If the melt can be identified, one specimen from each melt is to be examined. In the case of slab glass produced by a continuous process, and for lots for which the melt is not identified, five random samples are to be selected by the inspector. In the case of slabs and chunks, if the sample is found to differ from the specification by 70 per cent of the tolerance, several additional samples must

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be selected. If any of these additional samples fail to meet the specifications, then twice this additional number are to be examined. In the case that any of the latter fail, the entire lot must be rejected. For molded blanks, the schedule of selection is dependent upon the size of the lot. If a lot consists of twenty-five or less, all must be examined, whereas if there are over one hundred, a selection of thirty-five suffices. In this case a single failure will be cause for the rejection of the lot. A supplier may inspect and resubmit any samples from a rejected lot which meet the specifications.

These specifications are adequate for the definition and control of various types of optical glass. One application was found in a wide-angle tank telescope, where the specification on the dispersion should be tightened. More detailed studies may reveal other cases where general specifications should be tightened for particular applications.

Two methods are available for the rapid inspection of optical glass. The normal refractometer is a rapid and reliable instrument, provided the pieces of glass are of such shape and surface finish as to be usable in this device. Some inspectors prefer the immersion method in which the piece of glass is immersed in a liquid of the correct index of refraction. Variations of the index in the fifth decimal place are discernible. Among the liquids which are more commonly used are monochloronapthaline with $n_D = 1.634$ and monobromonapthaline with $n_D = 1.655$. These liquids may be mixed with mineral oil to adjust the index to the specified value.

The actual sampling technique used by various inspectors differs considerably from that called for by the specifications. The products of a new manufacturer or supplier generally receive 100 per cent inspection, whereas those from a previously known manufacturer, whose record has been good, will receive only a spot check for record purposes. This technique is

TABLE 1

		Tolerances of n_D		Tolerances of ν	
	Type of glass	Values	(plus or minus)	Values	(plus or minus)
511-635	Borosilicate crown, BSC-1	1.5110	0.0010	63.5	0.5
517-645	Borosilicate crown, BSC-2	1.5170	0.0010	64.5	0.5
513-605	Crown, C	1.5125	0.0010	60.5	0.5
518-596	Crown	1.5180	0.0010	59.6	0.5
523-586	Crown, C-1	1.5230	0.0010	58.6	0.4
529-516	Crown flint, CF-1	1.5286	0.0010	51.6	0.5
541-599	Light barium crown, LBC-1	1.5411	0.0010	59.9	0.5
573-574	Barium crown, LBC-2	1.5725	0.0015	57.4	0.5
574-577	Barium crown	1.5744	0.0015	57.7	0.5
611-588	Dense barium crown, DBC-1	1.6110	0.0015	58.8	0.4
617-550	Dense barium crown, DBC-2	1.6170	0.0015	55.0	0.4
611-572	Dense barium crown, DBC-3	1.6109	0.0015	57.2	0.4
562-510	Light barium flint, LBF-2	1.5616	0.0015	51.0	0.4
588-534	Light barium flint, LBF-1	1.5880	0.0015	53.4	0.4
584-460	Barium flint, BF-1	1.5838	0.0015	46.0	0.3
605-436	Barium flint, BF-2	1.6053	0.0015	43.6	0.3
559-452	Extra light flint, ELF-1	1.5585	0.0015	45.2	0.3
573-425	Light flint, LF-1	1.5725	0.0015	42.5	0.3
580-410	Light flint, LF-2	1.5795	0.0015	41.0	0.3
605-380	Dense flint, DF-1	1.6050	0.0015	38.0	0.3
617-366	Dense flint, DF-2	1.6170	0.0015	36.6	0.3
621-362	Dense flint, DF-3	1.6210	0.0015	36.2	0.3
649-338	Extra dense flint, EDF-1	1.6490	0.0015	33.8	0.3
666-324	Extra dense flint, EDF-50	1.6660	0.0015	32.4	0.3
673-322	Extra dense flint, EDF-2	1.6725	0.0015	32.2	0.3
689-309	Extra dense flint, EDF	1.6890	0.0015	30.9	0.3
720-293	Extra dense flint, EDF-3	1.7200	0.0015	29.3	0.3

Note. Each molded blank or glass plate shall be homogeneous in composition. The above tolerances are not to be construed as permitting any measurable variation in the refractivity between different portions of the same piece of glass.

[redacted]

probably more conducive to rapid inspection than the one specified. It requires, however, considerable judgment on the part of the inspector.

Striae

Optical glass is subject to many defects introduced during the manufacture. The most common defects are striae, color, and inclusions. Poor annealing of the glass produces objectionable strain. The method of grading these defects during the inspection of the glass depends upon a comparison between the individual piece under inspection and a group of representative, graded samples. In the case of striae, the grades and their description are shown in Table 2. Since the requirements with

Table 2

1. Grade AA containing no striae, streaks, or cords, as defined by the contract or order under which the material is being procured.
2. Grade A containing no visible striae, streaks, or cords, when examined by the various methods described in the specification.
3. Grade B containing striae which are light and scattered when used in the direction of maximum visibility. Using the method described below, these striae are just above the limit of visibility of the human eye.
4. Grade C containing striae when viewed in the direction of maximum visibility. It is required that the striae must be slight when viewed by the acceptable devices described below, and must be sensibly parallel with the face of the plate under inspection. In general, it is regarded that Grade C glass is a form of rolled plate.
5. Grade D containing more and heavier striae than Grade C, and with the striae oriented sensibly parallel with the face of the plate. Grade D glass is intended to be rolled optical glass of the poorest acceptable grade.

respect to striae are more strict in some cases than in others, a part of the specification depends upon the ultimate use of the glass. Table 3 lists the acceptable striae graded for each of the various optical components manufactured for use by the Government. In general, each piece of glass must be inspected for striae except in the exceptional case in which molded blanks have been pressed from previously inspected glass. The specifications on striae as well as on other defects of this type are somewhat arbitrary since no data are available to indicate the effect on the performance of telescopes and periscopes of striae in individual optical components. A device such as the KDC apparatus or the resolution striaescope should

Table 3

The optical part	Acceptable striae grade			
	A	B	C	D
Prisms				
Abbe	X			
Amici	X			
Dove	X			
measuring wedge	X			
Penta	X			
Porro	X			
Leman	X			
rhomboid	X			
binoculars (6x30) (7x50)			X	
ocular	X			
all others		X		
Eye lens				
binocular (6x30) (7x50)				X
telescopes (1-power approximately)				X
all others			X	
Reticles			X	
Field lens				
binocular (7x50)			X	
binocular (6x30)*			X	
telescope, 1-power*			X	
all others			X	
Collective			X	
Mirrors				
first surface			X	
second surface		X		
Windows			X	
Erecting lens				
telescopes (1-power to 3-power)			X	
telescopes (1-power approximately)*			X	
Objectives				
binocular (6x30)			X	
binocular (7x50)			X	
telescopes (1-power to 3-power)			X	
all others		X		

* These may be made from Grade D when approved by the bureau or agency concerned.

Note. Laps, folds, stones, or firecracks shall be limited to the depth of one-half of the grinding stock of the blank. In glass containing striae, the blanks shall be formed in such a manner that the path of light shall be approximately normal to the plane of the striae, except that for the Navy Bureau of Ordnance, no firecracks shall be permitted.

be used to examine a number of telescopes made from components containing various degrees of striation to determine the relation between the amount of striation and reduced optical performance. The specification should be rewritten on the basis of these studies and should be based upon the effect on performance of the instru-

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ment rather than upon the appearance of the glass.

It is current practice to examine each piece of optical glass for striae by one of two methods. The direct view striaescope is a device in which the striations appear in the field of a collimated

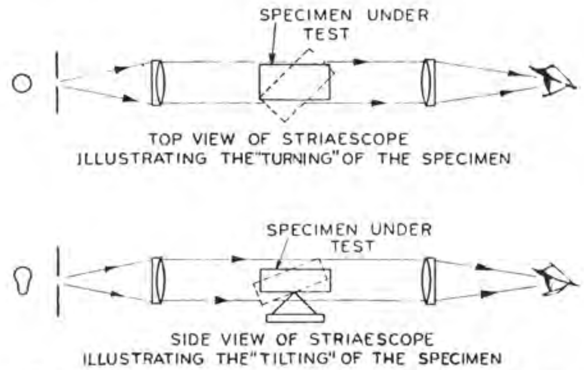

FIGURE 1. The striaescope for the inspection of slab glass.

light beam as observed through a small telescope. Figure 1 illustrates the optical arrangement in a direct view striaescope. An instrument which is somewhat easier to use is the projection striaescope illustrated in Figure 2. A representative sample of three types of striations appears in Figure 3. In all cases, striations are seen by virtue of the Fresnel reflections produced at the boundary of the striae. Most inspectors prefer the projection method

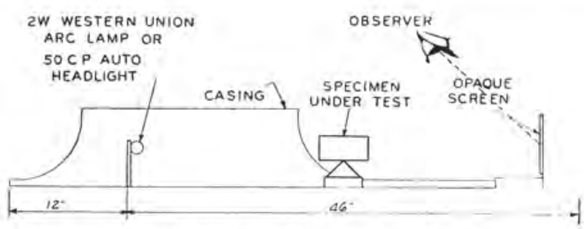

FIGURE 2. A projection striaescope.

in which the bands produced by the striations in the sample are compared with those of the standards.

In practice, the grading of striations of Types A and B is fairly straightforward. However, Types C and D are not so easily distinguished. As an example, if in a certain lot of glass, all pieces contained striations of Grade C, 50 per cent of them would be classed as D. The technique of using standards for comparison is very difficult if the standards are of different manufacture than the samples.

The method of inspection appears to be adequate to determine compliance with the specifi-

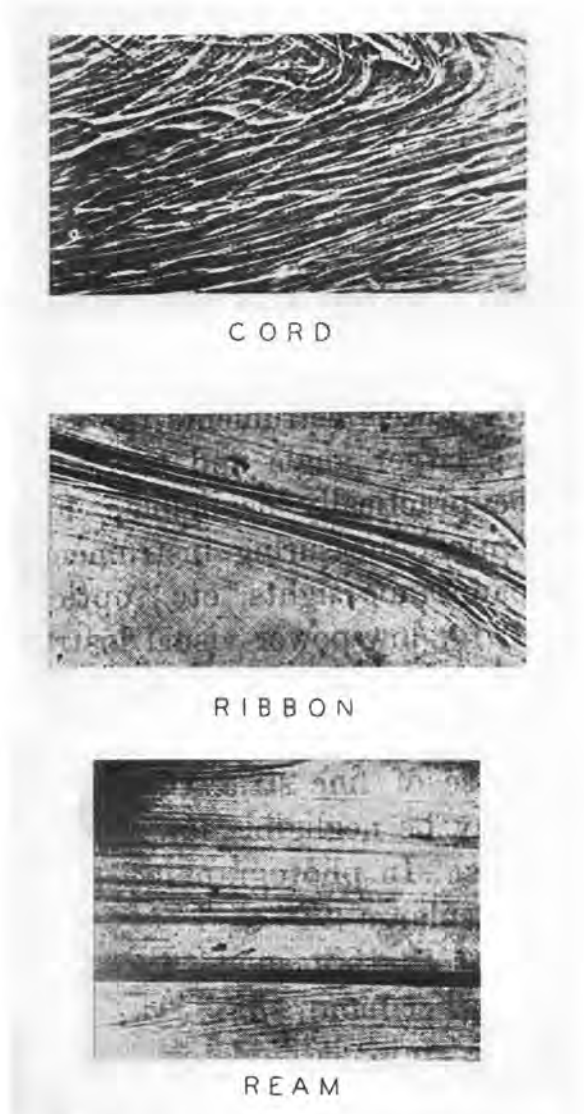

FIGURE 3. Inspection of slab glass for striae at Frankford Arsenal.

cations, but, as pointed out, the specifications themselves are open to serious question. Of one fact there appears to be little doubt, and that is that very heavy striations are optically undesirable, although there appears to be little data to support even this supposition.

In one particular case, certain modifications

[redacted]

should be made in the specification concerning the method of inspection of molded blanks. These blanks have a skin which makes it very difficult to inspect them for striae. The skin should be removed before the inspection.

Inclusions

The specifications and inspection methods for the evaluation of inclusions such as bubbles, seeds, and stones depend upon separating the ultimate uses of the glass into three classes, namely, reticles, field lenses, and others. In the case of reticles or other elements in the focal plane, it is required that no bubbles, seeds, or stones over 0.0004-in. mean diameter be present. Field lenses which are nearly in focus for the observer must be of higher quality than lenses in which such inclusions act only as light scatters. More than one bubble of 0.003-in. average diameter per cubic inch of glass is cause for rejection of glass for use in field lenses. For other uses, defects of this type may not exceed 0.1 per cent of the total area for each 10 cm. of light path. In addition, the number of bubbles may not exceed one per cubic centimeter, and finally no defect may exceed 0.021-in. mean diameter.

The inspector peers into the piece of glass, illuminated by a test lamp, and compares the defects with a set of standards. He must make mental corrections for variations of volume and thickness between the sample and the standards. In some cases the glass is immersed in a fluid to make the defects more easily seen.

Except for reticles, for which the specifications must be very exacting in order that the field be clear of undesirable spots, the requirements are based on the ability of the industry to produce glass of the indicated quality. In this case, as with striae, there is no well-established connection between the size, appearance, or number of inclusions in the components and the degradation of the performance of the completed instrument. What is needed is not only an objective test method but also a method related to performance rather than the glass industry's abilities.

Color and Dimensions

Light absorption and color are two qualities of optical glass which are either not specified in amount or are required to be absent. The governing principle is that if absorption or color can be detected the piece is rejected. The denser flints are, however, permitted to be slightly yellow.

Slab glass must be flat and of the thickness specified for the particular application. In general, the tolerances permit +2 and −0.0 mm for slabs up to 20 mm. Plates over 20 mm thick may be 4 mm oversize. Molded blanks must have grinding stock both on the surfaces and on the diameters.

Strain

Optical glass which has not been properly annealed contains permanent strain. This defect may be a source of trouble both in the final behavior of the optical elements produced from the glass, because of the presence of birefringence, and in the preparation of blanks for lenses or prisms because of the difficulty of cutting a badly strained piece. In the case of slabs of optical glass which are to be cut up and used in the manufacture of pressings, the glass must be sufficiently annealed to prevent breakage during handling, storage, and shipment, and to permit the cutting without shattering of blanks with straight edges. All other pieces of glass are required to be free from strain to the extent that the relative retardation of sodium light shall be less than 10 $m\mu$ per centimeter. Figures 4 and 5 show a typical apparatus now used for the inspection of samples for strain. The inspection consists of classifying the samples in polarized light by a comparison with one of a group of specimens containing known amounts of strain.

The practical effect of strain upon the optical behavior of lenses and prisms has not been investigated, but this question does not seem to be very important, since in a group containing a large number of pieces of glass examined during this study no pieces were found to have permanent strain of more than half the permitted amount. The introduction of a quartz wedge into a device for testing strain would permit the direct measurement of the amount of strain. Such a device was made up and utilized for the actual inspection of a sample number of pieces by a government inspector who reported that he acquired considerably

[redacted]

more confidence in such a direct quantitative measurement than he had in the older qualitative comparison method. The older method does have an advantage in that it permits a large number of pieces to be compared to a calibrated sample at once and with a single glance.

4.2.2 The Inspection of Optical Parts

LENSES

Physical Dimensions. The specifications of the dimensions of finished but unmounted lenses are included on the optical drawing. In general, the normal specification calls for an angle of 45 degrees to the edge.

Types of *go, no-go* gauges are in frequent use for checking the dimensions of lenses. Direct measurement with micrometers and dial-type gauges enjoys considerable popularity, particularly among company inspectors. A lens cell of nominal dimensions is often used as a gauge. The lens is placed in the cell and the retaining ring run up against a shoulder. The accuracy of the lens dimensions is then judged by the "rattle." The use of *go, no-go* gauges on the thickness offers more chance of injuring the surface than does the dial-type instrument.

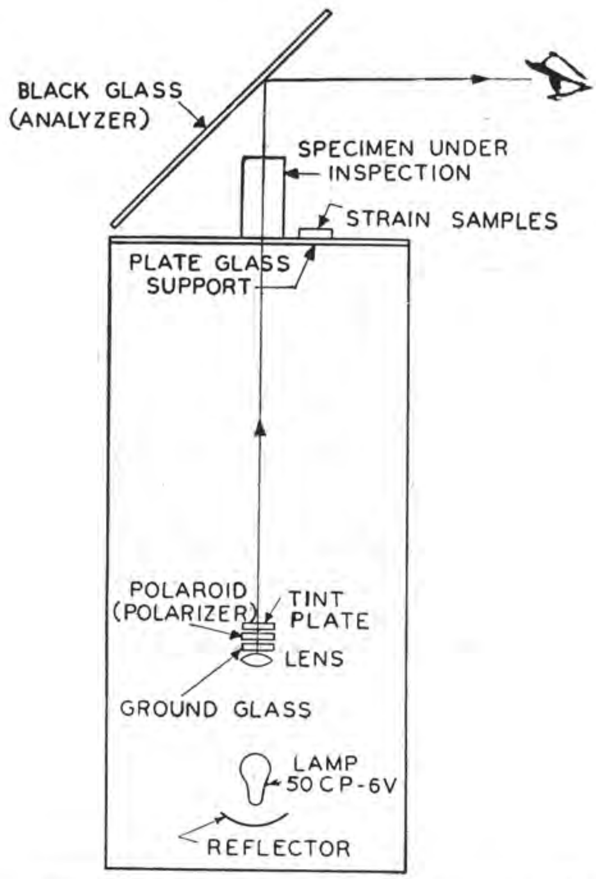

FIGURE 4. An apparatus for the inspection of strain.

FIGURE 5. Inspection of slab glass for strain at Frankford Arsenal.

the tolerances are also shown and are usually negative in the amount of about 0.001 in. per inch of diameter. The various dimensions specified are the diameter, the axial, and the edge thickness. Most lenses are edge chamfered and

Centering. Not only must a lens have the proper diameter, but this diameter must be centered on the optical axis of the lens. In the case of two or more cemented elements, each element must be centered so that its optical

[redacted]

axis coincides with the mechanical axis of the assembly. The centering error may be divided into two parts: the angle between the optical and the mechanical axis and the displacement of one with respect to the other. The latter error results in a variation in edge thickness and is covered in the previous specification. The standard specification calls for a departure in concentricity of less than 3 min of arc for all lenses, but oculars may be in error by as much as 6 min.

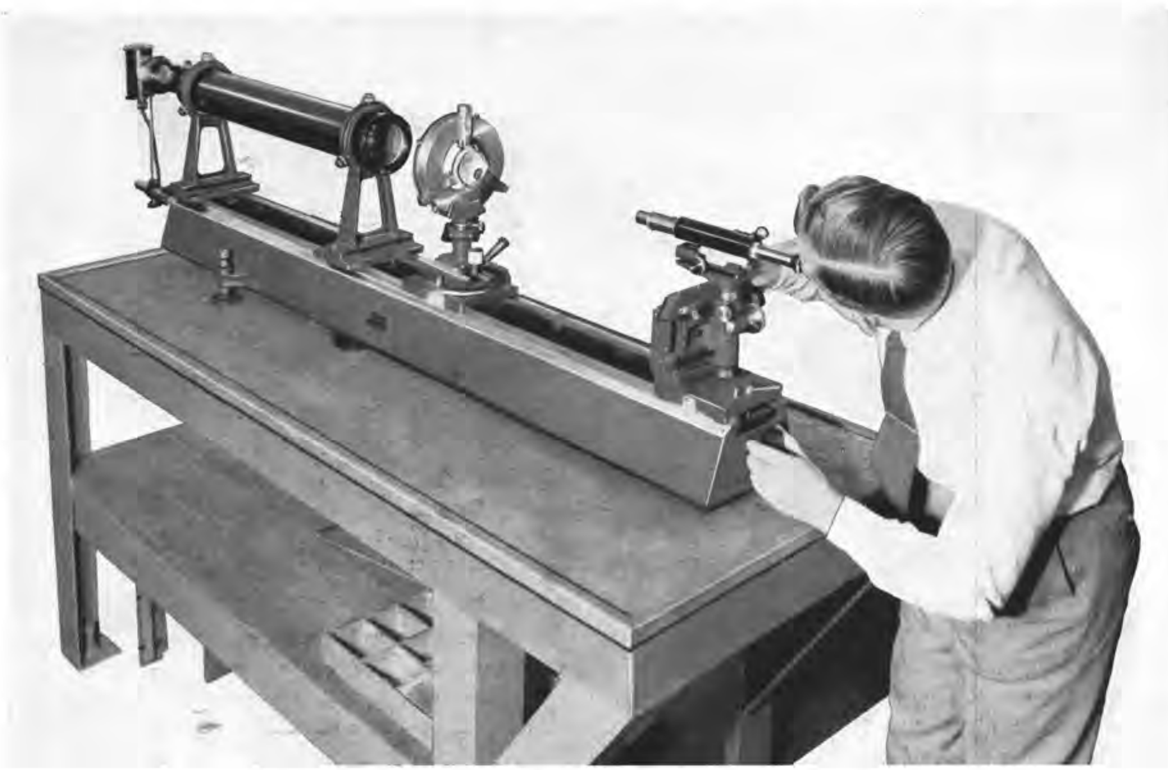

FIGURE 6. A lens bench for the determination of focal length.

For inspection, the lens may be mounted by its edge on a rotating collet. The motion of the optical axis may then be observed by viewing an object through the lens. Conversely, the lens may be mounted by cups against its surfaces. A microscope focused on the edge permits observation of any motion resulting from lack of concentricity. The second method is to be preferred for it facilitates accurate measurement of the error.

On the whole, the specifications and inspection methods for the dimensions of lenses are quite satisfactory. The tolerances are not only established within the ability of the production methods but are also readily measured for inspection. The lack of concentricity in lenses is known to have profound effect on the performance but the exact numerical values of the tolerances necessary for performance quality in line with other tolerances is not known. This factor is very important and a careful study of the matter should be made.

Focal Length. The principal optical attribute of a lens is its focal length. The equivalent and back focal length are both specified on the drawing covering the particular piece. Two per cent is a standard tolerance. In spite of the variety of devices in actual use, all the inspection methods utilize a form of optical bench. Figure 6 illustrates a conventional bench set up to measure the focal lengths of lenses. Any such device consists of a collimator, a lens holder, and an eyepiece or microscope fitted with a scale. A pattern at the focus of the collimator is focused in the microscope. The distance from the lens to the focal plane of the eyepiece or microscope is the back focal length.

[redacted]

One manufacturer marks the back of the lens with a glass marking pencil and starts each measurement by focusing on this mark. Another sets up a "sectional" instrument and adjusts the focus for a lens of the correct focal length. This lens may then be quickly replaced with those under test. The required motion of the microscope to restore sharp focus gives the error directly. A setup of this type for testing binocular objectives appears in Figures 7 and 8. A refinement on this device allows the objective to be rotated so that the concentricity and the focal length may be measured at the same time. In all the devices now in use, the focal length is determined for the best focus situation in which the lens is to be used. As examples, eyepiece lenses are not to be tested for definition separately but in an assembled eyepiece; collectors are to be tested not at full aperture but at the aperture utilized in the instrument. The test of definition depends upon a comparison with standard units. Frequently, the acceptance standard is selected by the government inspector from regular production at the facility concerned.

Most often the test for definition is simply an examination of the sharpness of focus and the contrast of the image formed by the lens or lenses with the aid of a high-powered microscope. It is obvious that this test may be made

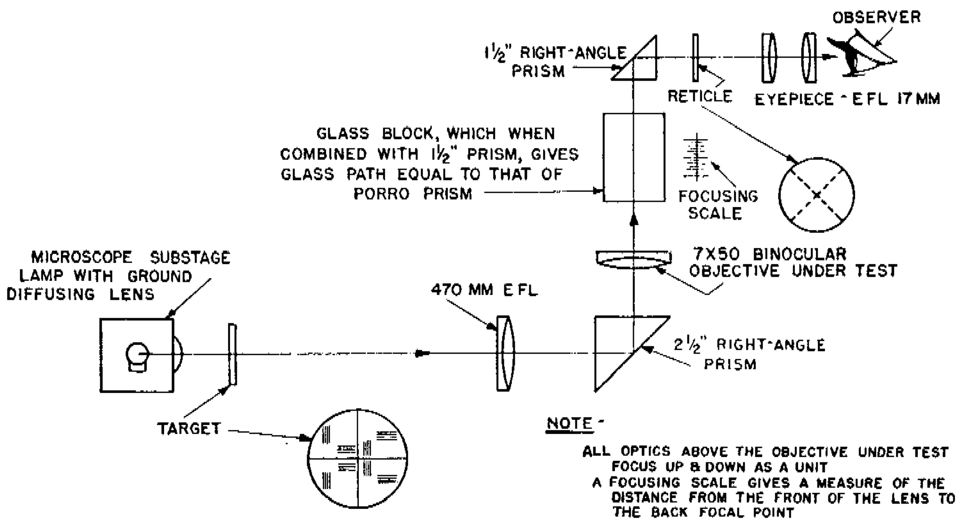

FIGURE 7. The focalometer.

over the entire aperture of the lens and not merely for the paraxial rays.

Although the specifications of focal length and the methods of inspection are satisfactory, the basis of the tolerance is again not well established. Here it appears that the requirement of precision is based more upon the ability of the industry to produce acceptable optics than upon the limits set by the overall performance of the instruments in which the pieces are to be used.

Definition. Each objective, collective, erector, and ocular must be subjected to a test for definition. The specification is so worded as to stipulate that the lens is to be tested in a fashion as nearly as possible approaching the at the same time and in the same machine as the previously described tests of focal length.

Of the various specifications so far discussed, the one concerning definition is probably the least satisfactory. It is far from quantitative, but without further development of testing procedures it cannot be improved on. Two instruments described in Section 4.3 could be utilized to place the determination of definition on a quantitative basis. The more useful of the two, in this connection, is the modified Michelson-Twyman interferometer. If this instrument were established as a basis for inspection, the specification could read: "The lens when tested in the Michelson-Twyman interferometer shall conform to the interferometer pattern indi-

[redacted]

cated on the detailed drawing of the given part, within plus or minus one interference fringe." The specified interference pattern may be the result of computation or the observed pattern produced by an acceptable lens. The tolerance should be based on a study of the effect of errors in each particular lens on the behavior of the complete system.

FIGURE 8. Device used by the Bausch and Lomb Optical Co. to inspect finished lenses for focal length.

The KDC apparatus, which is now used for the inspection of complete instruments, could be used for the testing of individual components and subassemblies. In this case, a KDC efficiency for each lens should be established. The most satisfactory test method would probably involve a combination of the optical element under test with a suitable system in which all the intended faults of the lens are compensated in exactly the same way as they would be in the instrument for which it is designed.

In many cases, individual lenses need not be tested for conformance to specification. Tests for axial thickness, focal length, and even definition on a quantitative basis could grade the lenses into groups. Proper selections of components from the groups could then be combined to yield assemblies whose performance would be acceptable. This procedure complicates the problem of spares however. Since the general problem of spares has not been examined, the relative merits of component spares versus assembly spares cannot be evaluated here.

Beauty Defects. Individual lenses are inspected for so-called beauty defects. These defects are of two shape types: scratches, long and thin; and digs, pits, and bubbles which are nearly circular. The permissible number of maximum size scratch-type defects in an optical system as determined by their combined length and location is shown in Table 4. The classification as to least, less, and most critical lenses refers to their positions in the instrument. Most critical lenses are those lying substantially in a focal plane, less critical are those lying near a focal plane, and least critical are those lying far from the focal plane. The classification numbers for each defect, 10 to 100, are determined by comparison with a set of standard samples. As in the case of seeds and stones in optical glass, these beauty defects are specified more upon their appearance than upon the effect which they may have upon performance. Since these defects result in the rejection of many optics which may be usable, experimental work is needed to determine their actual influence on performance. These may be in the form of psychological experiments, or experiments showing actual deterioration in some desirable optical property.

PRISMS, WEDGES, AND WINDOWS

Angles. Many of the specifications and inspection procedures are precisely the same for prisms, wedges, and windows as for lenses. There is no point here in reviewing this material. In one particular case, that of the physical dimensions, a new type of specification must be added. For prisms and wedges the various angles must be specified and inspected while for windows the degree of parallelism must be inspected. Figure 9 illustrates the use of the dial gauge for the inspection of the critical dimensions of prisms. This instrument seems to be particularly useful in this connection, especially when it is provided with the type of fixtures illustrated in Figure 9. Many methods are now utilized for the inspection of prism angles. The

most successful of these utilize supplementary optical systems in which the defect is magnified by the displacement of an image. Two instruments merit special mention. One is the projection equipment illustrated in Figure 10. A wide variety of such devices may be utilized to inspect prisms of various shapes. In the particular case of binocular prisms, it is obvious that slight errors in the angles of one prism may be compensated for by errors in the angles of a second prism. If the prisms are properly paired, their optical behavior as an assembly is in every way as satisfactory as it would be if both prisms were perfect. The projection equipment may be so constructed as to test prisms in pairs. By far the most useful instrument for the testing of prisms, but one which has not as yet enjoyed very great popularity, is the interferometer. This device permits a quantitative determination of the accuracy either of individual prisms or prism combinations. It may be used to measure the roof angles on roof prisms as well. A typical interferometer setup appears in Figure 11.

In the case of windows, the most common procedure is simply to examine a target through the window with a fairly high power telescope. If no deviation is observed as the window is inserted and withdrawn from the optical path, the window is acceptable. For critical wedges such as are used in heightfinders, the interferometer is the most common inspection instrument. The method consists of adjusting one of the mirrors of the interferometer by means of a master wedge of acceptable angle.

TABLE 4

Total length of scratch-type defects permitted for least critical lenses

80 scratch ¼ diameter of element
60 scratch ½ diameter of element
40 scratch ¾ diameter of element
20 scratch 1 diameter of element
10 scratch 5 diameter of element

Permitted size of defects in less critical lenses

Beam diameter (mm)	For central zone ½ diameter of surface scratch	dig	Outer zone scratch	dig
Over 7	80	70	80	70
5-7	80	50	80	50
4-5	60	40	60	40
3.2-4	60	30	60	40
2.5-3.2	40	20	60	40
2.1-2.5	40	15	60	30
1.6-2.1	30	10	40	20
1.0-1.6	20	5	40	15
0.6-1.0	15	3	30	10
0.4-0.6	10	2	20	5
0.2-0.4	10	1	15	3

Permitted size of defects in most critical lenses

Beam diameter (mm)	Magnifying power	Focal length	For central zone ½ diameter of surface scratch	dig	Outer zone scratch	dig
0.2	20-10	12.5-25	10	1	15	3
0.4	10-5	25-50	10	2	20	5
0.6	5-3.3	50-75	15	3	30	10
1.0	3.3-2	75-125	20	5	40	15
1.6	2-1	125-250	30	10	40	20

Definition. There is a specification concerning the resolution required for prisms, wedges, and windows. The actual values of the definition depend upon the aperture of the particular

instrument and are generally stated on the optical drawing. In practically all cases, a resolution test target set at some appropriate distance is viewed by means of a high-powered telescope. The amount of magnification depends upon the aperture of the prisms and is at least 50× for each inch of aperture. If the various optics are tested on the interferometer for accuracy of dimensions, the patterns observed are also a good measure of the definition.

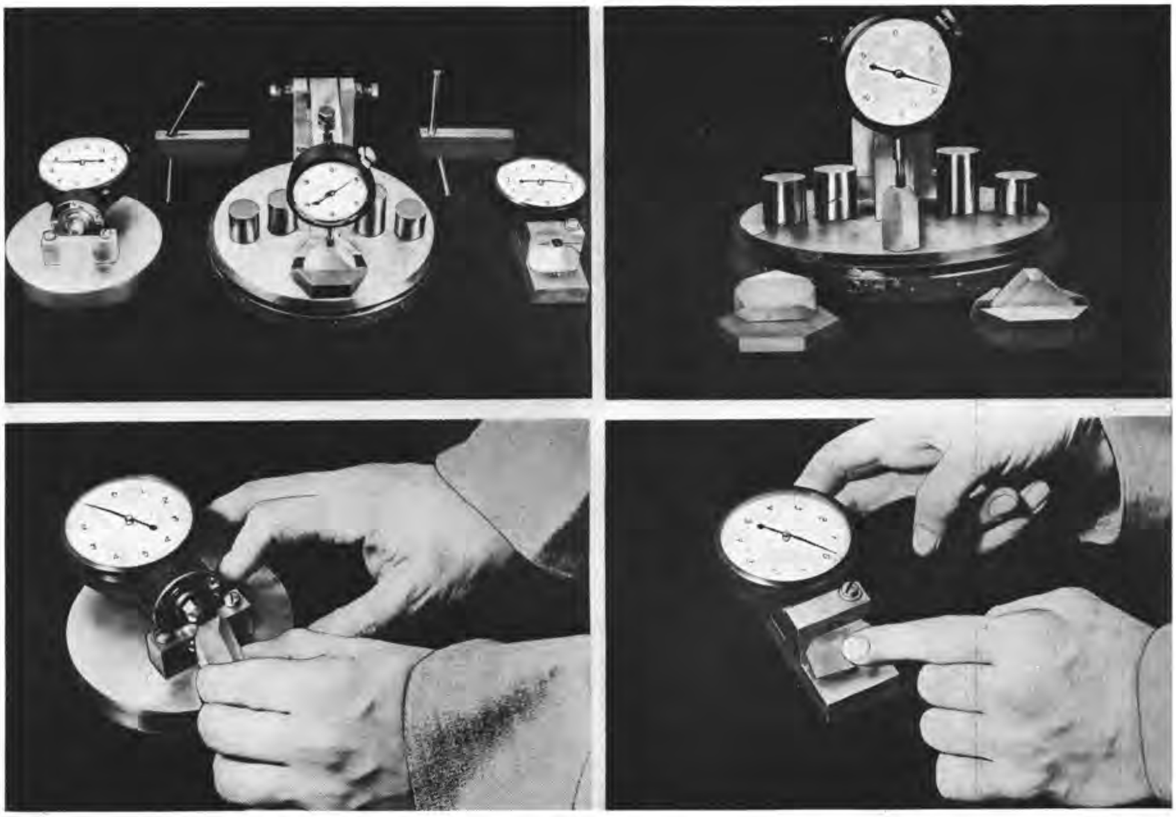

FIGURE 9. Dial gauges used to inspect the physical dimensions of prisms.

RETICLES

A rather specialized type of optic used in military instruments is the reticle. Besides its obvious optical characteristics, physical dimensions, parallelism, and beauty defects, which are specified and examined by the methods already described, reticles must be inspected for the location, magnitude, and uniformity of graduations. The specifications cover not only the uniformity of width and depth of the rulings, but also absence of breaks (no more than three per reticle are allowed, and none wider than one-half the width of the line) and the exact location of the markings. In general, a toolmaker's microscope, such as that illustrated in Figure 12, is utilized for the inspection. A center determined by the outer edge of the piece is the origin of all measurements, and each graduation is measured with respect to this origin. The operation of inspecting reticles is a very tedious task and must be entrusted to experienced inspectors. In view of the great growth of projection inspection methods in the small parts industries, it is somewhat surprising to find that this method is not utilized here. A comparison of an enlarged projected pattern of the reticle could be made directly with a standard pattern and would require considerably less time and experience.

FLATS

In some larger instruments, optically flat mirrors are employed as substitutes for prisms.

[redacted]

It is common to specify either the number of interference rings which may exist between the part under inspection and a master flat, or the astigmatism produced when the mirror is utilized at a 45-degree angle of incidence. Conformance with the latter of the two specifications is easily measured by actually examining a test object with a high-powered telescope and the optical flat set at 45 degrees before the objective. The measurement consists of determining the difference in best focus for the vertical and horizontal positions of the test object. The checking of an aluminized flat against a master flat is very difficult since any damage to the aluminum coat is cause for rejection. The interferometer is probably the most practical method for the checking of optical flats.

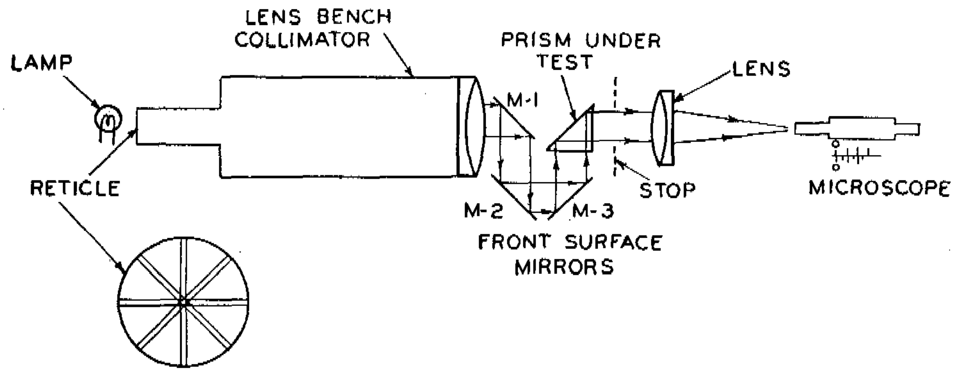

FIGURE 10. Schematic diagram of mirror assembly used in lens bench measurements on M-10 periscope head prism.

4.2.3 The Complete Instrument

Because of the great variety of optical instruments manufactured for and used by the Armed Services, it is impossible to consider them all individually. Inspection of three types, the tank telescope, the tank periscope, and binoculars, was studied most completely during the survey and the specifications and inspection methods for these instruments will be described in some detail.

DEFINITION

By far the most important characteristic of any optical system is the quality of the image which it produces. Yet, except for the M-71 tank telescope, the specification of this important quality is very obscure. For example, the specification for the image quality of 7x50 binoculars reads in part: "The optical system shall be free of distortion and any residual distortion be compatible with the best correction of the other aberrations." The meaning of this type of specification is obscure and impossible of application except in the judgment of some individual inspector. In the case of binoculars, the situation is somewhat better since the specification states also that the limit of resolution within one degree of the center must not be less than 4 sec of arc for a standard black line chart.

The M-10 periscope consists of two optical systems, one of unity power and one of 6×. The specification requires that the unity-power portion produce images which "shall be clear, well-defined and free from objectionable imperfections." The 6× section must be "practically free from distortion, astigmatism, curvature of field, coma, chromatic and spherical aberration." These specifications are desirable goals for the optical designer, but are not proper requirements upon which to control production.

By contrast, the specification for the M-71 telescope reads: "No telescope shall have a KDC efficiency less than 75 per cent on the axis." Here is a quantity readily measured and free from personal judgment on the part of the inspector. Moreover, the use of this specification and inspection method led to an improvement of 20 per cent, on the average, in the efficiency of telescopes produced by those facilities

which formerly produced the poorest telescopes.

The KDC apparatus, about which considerably more will be said shortly, may be seen in Figures 23 and 24. The efficiency is simply the ratio of the limiting distance for resolution of a standard target with the telescope under test to the distance for resolution of the same target with a telescope of high quality having the same entrance pupil as the one being tested. In the case of the M-71 telescope, the efficiency is related to a simple telescope of good design and high quality, so that the resolution on the axis is limited only by the entrance pupil. The efficiency could equally well be related to a perfectly made M-71 telescope. The difference in the two efficiencies would be the loss of definition imposed by the design. The KDC apparatus has been demonstrated to be quite free of a personal equation and thus its results are desirably quantitative.

One additional advantage of a purely quantitative method of inspection has not as yet been pointed out. Careful investigation may show that certain common types of mistakes in assembly are characterized by definite values of efficiency. For these cases, then, the inspector will not only pass on the acceptability of the instrument, but, if it is rejected, will point out where the fault lies as well.

The inspection of binoculars and tank periscopes is usually made by examining the resolution of a standard target through the instrument under test with the aid of an auxiliary magnification of 3$\times$ to 6$\times$. Figure 13 shows an inspector examining binoculars. The entrance pupil of the viewing telescope is 7 mm, to match the pupil of the eye under conditions corresponding to normal use. On the basis of what he can see, the inspector judges whether the instrument is acceptable. Probably few good instruments are discarded and few poor instruments are passed by this method. The borderline cases, however, are difficult to judge. No doubt at some times instruments are rejected which are actually better than those accepted at other times by the same inspector or by other inspectors.

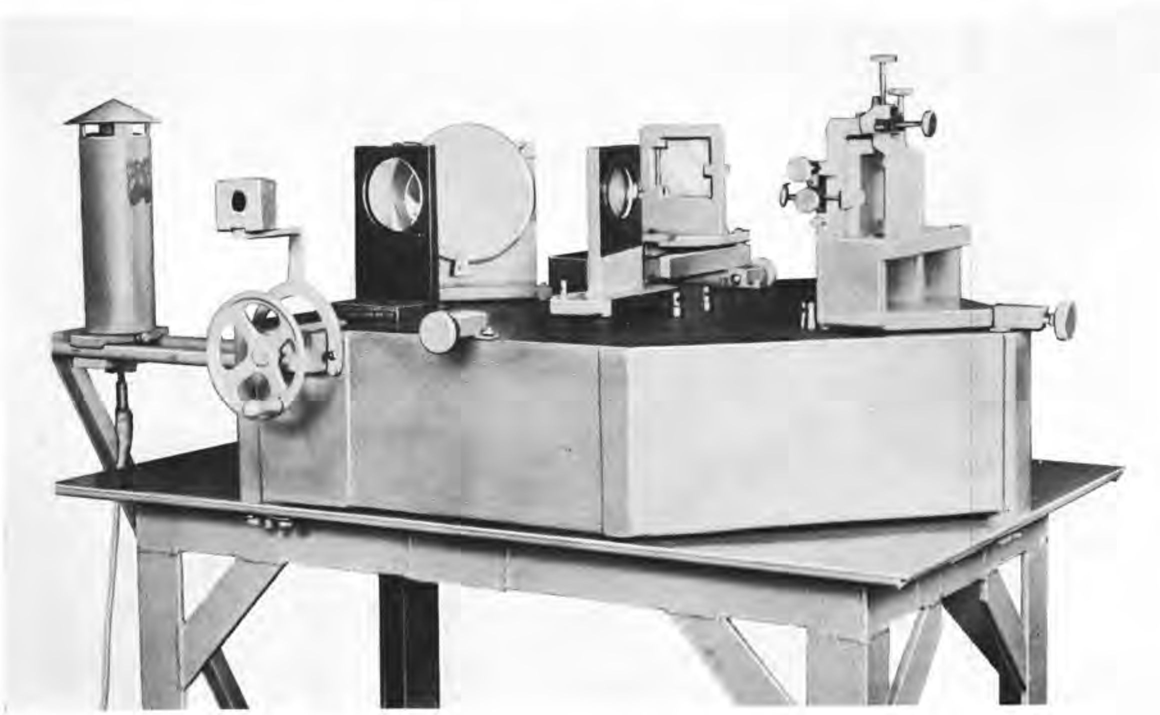

FIGURE 11. The Frankford Arsenal interferometer.

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MAGNIFICATION, ENTRANCE, AND EXIT PUPILS

For the M-71 telescope, the magnification must be within 10 per cent of 5×, while for the 7x50 binoculars, it must be 7× plus or minus 2 per cent. In addition, the magnification of the

FIGURE 12. The inspection of reticles by means of a toolmaker's microscope.

two systems of a binocular may not differ by more than 2 per cent. It is to be pointed out that the focal length of the objective, the eyepiece and erectors, the linear calibration and the angular specification of the reticle, and the magnification are all related. The tolerances should likewise be related. There is no point in specifying any one of these quantities to a higher accuracy than is required by this interrelation.

The present satisfactory method of testing telescopic systems for magnification, where it is specified, depends on a micrometer measurement of the exit pupil when the entrance pupil is limited by a stop of known size.

For the M-71 telescope, the exit pupil is not specified in the same way that the entrance pupil and magnification are. Numerically, the value of the exit pupil for this instrument is 0.276 in. and the eye distance is required to be 1.051 in. During the measurement of the entrance or the exit pupil, the eye distance may be checked by observing the distance between the focal plane of the observing microscope and the eye lens when the exit pupil is in sharp focus. The procedure is to focus first on the surface of the eye lens and then displace the microscope along the axis until the exit pupil is in sharp focus. The displacement is the eye distance.

For binoculars, the exit pupil is specified as not less than 50 divided by the magnification. In this case the specification is more explicit in that it requires the exit pupil in the center of the field to be circular, except in so far as the area may be reduced by a cord if the reduction does not exceed 2 per cent. At the edge of the specified field (24 degrees, 10 min) the minimum dimension of the exit pupil must not be less than 45 per cent of the diameter of the central pupil. The measurement is made in precisely the same manner as the previously described measurements involving the exit pupil with the one refinement that the microscope must be so mounted as to rotate about an axis through the exit pupil of the instrument.

In general, these specifications and methods of measurement which involve the entrance pupil, the magnification, and the exit pupil are

FIGURE 13. The inspection of binoculars for definition.

quite satisfactory. It must be pointed out, however, that the measurement of an off-axis exit pupil is very difficult since the bounding surfaces are not in the same plane and therefore

[redacted]

cannot be brought into sharp focus simultaneously. The actual measurement will depend to some extent upon the opinion of the inspector.

The M-71 telescope is not covered by a specification relating to the size of the true field, but nevertheless at all production centers a test of the field is made. The design indicates a true field of 13 degrees and present practice requires a field of 12.5 degrees. The 7x50 binocular must mission. The specification is adequate and the method now employed is straightforward and quantitative.

Mechanical Features

Classed here as mechanical features are the specifications covering cleanliness, collimation, and weatherproofing. The specification for cleanliness is in the form of a description of the treatment to be applied to a telescope, peri-

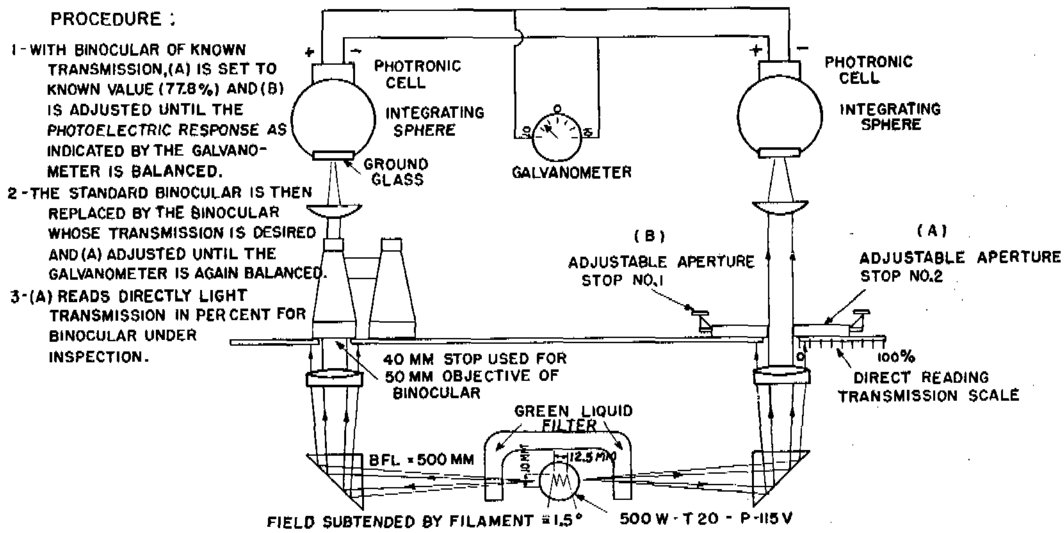

FIGURE 14. Photoelectric photometer for the inspection of light transmission.

have a true field of not less than 7 degrees, 10 min. For both instruments, the inspection procedure involves the viewing of a target which may be either in the form of a scale calibrated in degrees or a large white circle of the required diameter. It is readily apparent to the inspector whether the field is sufficient.

Light Transmission

The M-71 telescope must pass not less than 62 per cent of incident white light. The binoculars are required to have a transmission of at least 74 per cent. There is no covering specification for the light transmission of the M-10 periscope, but an occasional instrument is inspected in order to insure that no long-term reduction in the quality is occurring. A comparison-type photoelectric photometer, such as is illustrated in Figure 14, is normally used for the determination of the percentage of transmission.

scope, or binocular, without traces of moisture, dust, or other substances appearing on the surfaces of the various lenses. It is now routine to shake and tap the instrument under test with a hard rubber rod and then to examine the surfaces of the various lenses from the objective and eyepiece ends. If dust is found in the instrument, it is very difficult for the inspector to localize the surface. The amount of illumination used in the inspection determines the size of the particles which are visible and, although it does not appear in the specification, a value of 300 footcandles on a uniformly illuminated field is standard practice.

The proboscope (see Sections 4.1 and 4.3.5) permits the examination of each internal surface in turn, so as to establish the location of any offending dirt or moisture. Such a device may save a number of otherwise rejected instruments since it is possible with its use to

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determine whether the defect is on a critical area of the lens or prism.

The optical axis of an M-71 telescope must coincide with the geometrical axis within plus or minus 0.25 mil. The geometrical axis is established by the spherical bearing surfaces of the collars on the telescope tube. Figure 15 shows a typical setup for the determination of collimation. V blocks supporting the telescope

FIGURE 15. Collimator used to determine true field, collimation, and reticle accuracy.

are adjusted so that the optical axis of an acceptable instrument coincides with the image of the collimator reticle. Test telescopes are then placed in the V blocks and the displacement of the image of the collimator reticle with respect to the reticle of the telescope is observed. Unfortunately, it appears that there is a good possibility that the setting for the standard telescope may be in error by an amount greater than the tolerance. Further, the specification relates only to the optical axis as defined by the markings on the reticle. The extent of misalignment of the various subassemblies is not specified or measured. A lack of collimation in one assembly may be balanced by a corresponding improper adjustment of another section, and since such a combination requires that the axial rays for the telescope as a whole traverse the subassemblies as off-axis rays, deterioration in the image quality results. Measurement of the KDC efficiency will show up such a fault.

Besides the normal collimation test for binoculars, similar to that just described, the relative positions of the optical axes of the two telescopic systems is specified. The specification requires that when two parallel pencils are projected into the two objectives of the binocular, the rays emerging from the two eyepieces shall be parallel within the following limits for any setting of the interocular distance: (1) The angle must be less than 14 min of arc in the plane perpendicular to that determined by the two entrant pencils. The rays must not diverge more than 28 min of arc nor converge by more than 14 min of arc in the plane parallel to the plane of the entrant pencils. Inspection of binoculars under this specification requires an apparatus similar to the one illustrated in Figure 16. The optical arrangement of this instrument appears in Figure 17. While the nature of the setup is obvious from the figures, the procedure requires some explanation. It is common practice to align one-half of the binocular so that the image of the collimator reticle formed by the binocular and observed through the auxiliary telescope is coincident with the image of the geometrical center of the reticle of the observing telescope. The image of the reticle of the collimator formed by the other half of the binocular is then displaced in the observing telescope by an amount which is a measure of the collimation. It is possible to provide the second auxiliary telescope with a reticle containing a figure whose extent is the limit set by the specification. The acceptability of the instrument under test is thus determined at a glance. An interesting and apparently very useful device for inspecting the collimation of binoculars is shown in Figure 18. The device was developed by the British and is used by them for this purpose. It has the advantage of requiring but one collimator and viewing telescope, but utilizes three flat mirrors. The adjustment is very simply made, as is shown in the figure.

In addition to the measurement of collimation of binoculars, the collimation must be maintained under set specified conditions of shock. Figure 19 is a schematic diagram of the shock test given to British binoculars in the National Physical Laboratory. The American specification calls for a similar test, but with the distance increased to 6 ft. If the instrument passes this test, a strong cord free from stretch, such as a sash cord, is tied around the hinge pin and the instrument is dropped 6 ft in such a manner that the fall is arrested by the cord.

The collimation must remain within the specification after these drops. These specifications of collimation appear to have grown with the industry. They are greatly influenced by the opinions which existed during World War I and it might be well worth while to conduct an investigation to determine the most suitable tolerances. It is of interest to note that the specification takes into account the fact that the human eyes are accustomed to examine objects from which there are divergent beams of light and unaccustomed to situations involving convergent beams of light.

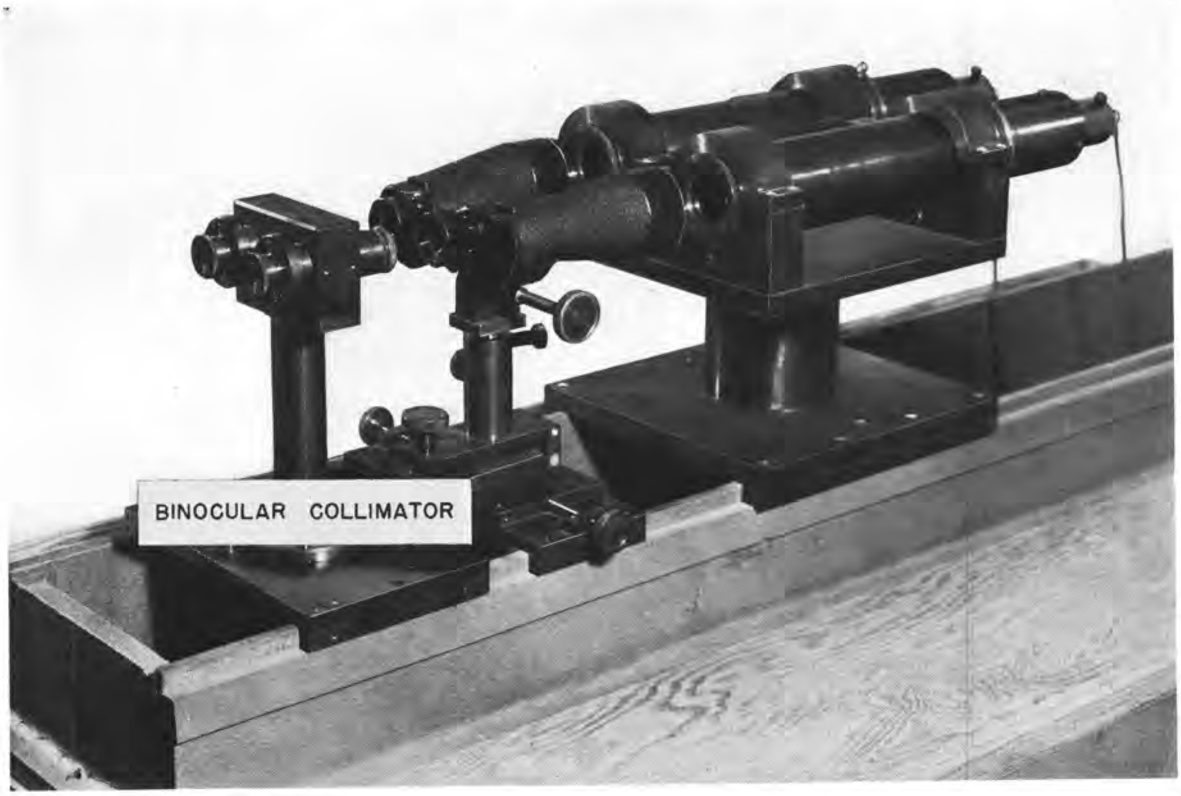


FIGURE 16. Apparatus for the inspection of binoculars for collimation.

The Reticle

An important part of most military optical instruments is the reticle. Much of the usefulness of military optical instruments, such as sighting telescopes, depends on its reticle. The graduations of the reticle must not only subtend the angles they are designed to represent but they must be in proper focus and be free from parallax. In addition, the vertical lines must be parallel to the vertical lines of the image. The accuracy of the graduations of the $6\times$ portion of the M-10 periscope is specified as ± 1 per cent plus 0.1 mil in elevation, and for the unity-power system ± 1 per cent plus 0.2 mil. For the M-71 telescope, the tolerance is ± 0.5 mil, and for binoculars, where they are equipped with a reticle, ± 3 per cent.

Substantially the same technique of inspection is used for each of these instruments. A collimated image of a standard reticle is compared with the reticle under test, sometimes with the aid of an auxiliary telescope. The reticle in the collimator is provided with double marks for each range mark. If all the marks on the inspected reticle fall between the corresponding marks of the test object, the reticle is acceptable.

The specification is sufficiently definite but is based more upon the difficulty of construction than upon the actual tolerance established by

[redacted]

field experience. In this connection, numerous complaints have been received which indicate that the graduations do not read the range accurately. It is recommended that these complaints be investigated to determine whether they arise from tampering in the field, inadequate inspection, or insufficient specification.

The reticle must be so placed in the instrument as to remove parallax for a target between 500 and 525 yd for the M-71, or 700 and 800 yd for the M-10. In addition, with the aid of a 3× auxiliary telescope, the reticle must be in sharp focus for a diopter setting of zero, ±0.25. For inspection, the instrument is placed in a collimator, sometimes the same one used in the previous inspection, whose reticle is optically placed at a distance corresponding to the center of the specified range. The use of a dioptometer greatly facilitates the inspection. This device, developed at Penn State, is described in Section 4.3.4.

The methods already described will also check the reticle plumb and image tilt. The specification of the M-71 telescope requires that the axes of the reticle shall be vertical and horizontal within 0.4 mil at the 400-yd mark when the locking pin is in a downward vertical position. The requirement for binoculars is such that the markings shall be correct with respect to the center lines of the objectives with the interpupillary distance set at 63 mm. The tilt shall not exceed one-half degree for all settings from 63 to 72 mm. In the case of the M-10 periscope, the reference is the vertical axis of the instrument. In addition to the plumb of the reticle, the image of a vertical line of a distant

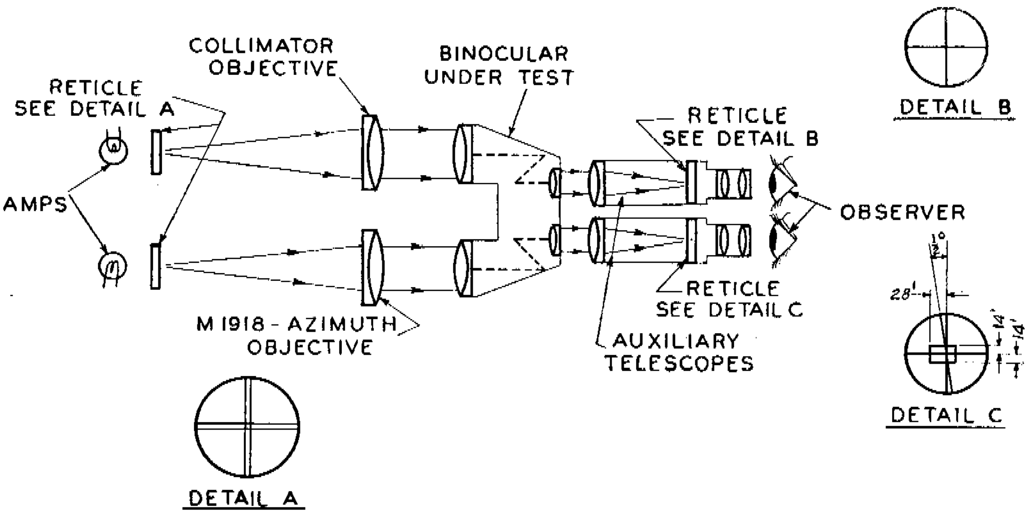


FIGURE 17. Schematic diagram of binocular collimator.

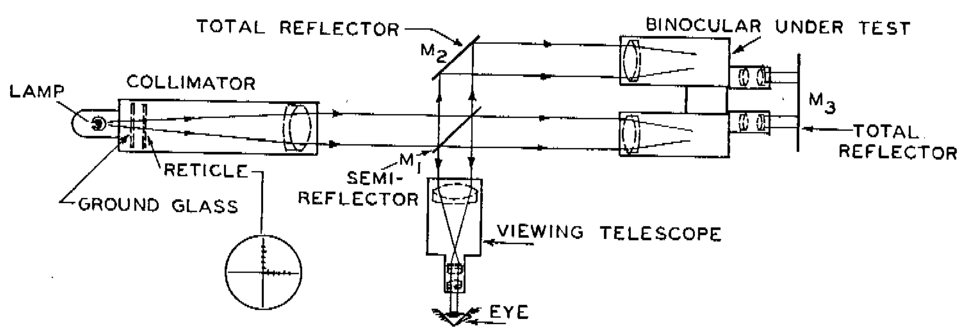


FIGURE 18. Schematic diagram of apparatus used to inspect binoculars for collimation at the National Physical Laboratory.

target must not deviate by more than 30 min from the reference.

WEATHERPROOFING

Since most military instruments must be used under all weather conditions, it is of considerable importance that the optical performance be not impaired by such conditions. The M-71 telescope and the M-10 periscope are subjected to a shower equivalent to a light rain for 5 min. Binoculars are actually immersed to a depth of 12 in. in a tank of water for 5 min. The instruments are examined after the test and again 24 or 48 hours later.

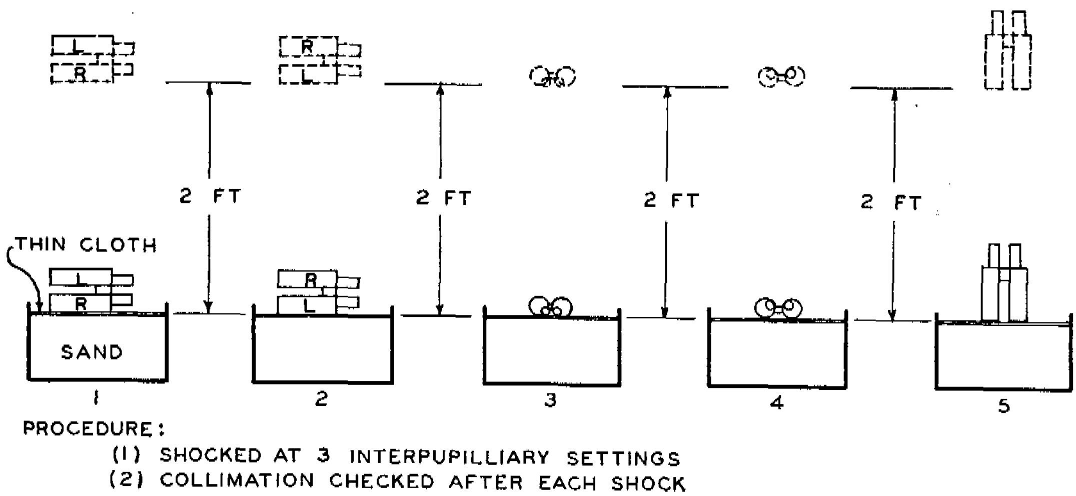


FIGURE 19. Schematic diagram of shock test for binoculars used by the National Physical Laboratory.

4.2.4 Summary Results of the Survey

The underlying philosophy of specifications and inspection of optical instruments for production control should be geared to the use to be made of the instrument. The specifications should not include factors of design or desirable results of design, but must be directed only toward the insurance of conformance to a fixed, acceptable design. Since it should be the inspector's duty to *measure* conformance to a given design and not to *judge* between one design or another, he must be provided not only with definite numerical specifications but quantitative means for the determination of conformance to these specifications. His judgment must not enter, for the instrument must stand or fall on the basis of its numerical performance.

It is a further desirable feature of inspection not only to determine agreement with specifications within the tolerance, but by measurement to determine the error. Two factors are to be noted here. The first is the concept of tolerance. Tolerances must be based upon real effects upon the performance and not upon any other factor. Many of the tolerances in present specifications are based upon custom, appearance, or the abilities of the industry. It is a natural desire to include only the best producible components, and from the point of view of a long-term improvement in the industry, this practice has advantages. On the other hand, many usable optics are now being discarded for the sole reason that the industry can do better. Examples are the questionable cases of striae, scratches, inclusions, and defective components which could be used by proper selection and matching. As a test, the compiler of specifications might ask himself how the variation of focal length, or thickness, or concentricity, or freedom from striae, of this particular lens affects the resolving power of the complete instrument. If the result of a change of ± 10 per cent in focal length, say, of a particular lens in a complex system makes no measurable change in the KDC efficiency, then such should be the

specification even though this lens could be made to a ± 2 per cent tolerance. The saving in production time and control may be considerable.

In order to aid in the solution of part of the problem set forth here, several new instruments have been developed. Their purpose is primarily to reduce to a quantitative basis the more important specifications and inspection methods covering the resolution of complete instruments as well as their components. At the close of World War II, considerable progress had been made in the application of these instruments. The entire production of the M-71 telescope is now controlled by the KDC apparatus. Great numbers of other instruments have been checked on this machine. The Michelson-Twyman interferometer has been used for certain individual checks by various manufacturers and is enjoying increasing popularity.

4.3 IMPROVEMENTS IN TESTING METHODS

As has been pointed out, one of the most urgently needed improvements in testing methods is the introduction of types of apparatus and methods so designed as to yield impersonal numerical results. These results, if they are to be of maximum usefulness, must be free from the judgment of the inspector and must not require a high degree of training or skill.

The most important single attribute of any optical instrument used as an aid to the eye is its resolving power. It is therefore highly desirable to have available a device which can measure resolving power. In the Thomas Young Lecture of 1935,[4] Fabry summarized the status of knowledge of the resolving power of the eye. He described equipment which could be used for measuring its resolving power under various conditions of target contrast, pupil diameter, and optical aid. It was apparent that under some conditions the overall resolving power was limited by the optical aid and not by the eye. Here, then, was a method for measuring the resolving power of an instrument which could perhaps be made independent of the eye. It was from this point of view that the KDC apparatus was developed at Pennsylvania State College under NDRC.

4.3.1 The Kinetic Definition Chart Apparatus

The resolving power of the eye has been found to be 4.5 sec of arc per inch of aperture for small diameters of the pupil. The resolution deteriorates for larger pupil diameters because of the optical errors of the eye. It is highly significant that the value 4.5 sec is actually superior to the value, 5.54 sec per inch, defined somewhat arbitrarily by the Rayleigh criterion, on the basis of diffraction theory. The resolving power is measured by the smallest angular separation of a set of parallel black bands separated by white bands of the same width which can just be resolved. The black and white bands, of which there are 8 to 20, are arranged in a square array. Such a target is known as a Foucault test object. A group of these objects was arranged so as to have the directions of the lines different in neighboring groups for use in the KDC apparatus. Generally, the objects are placed around a central numeral which is used for focusing.

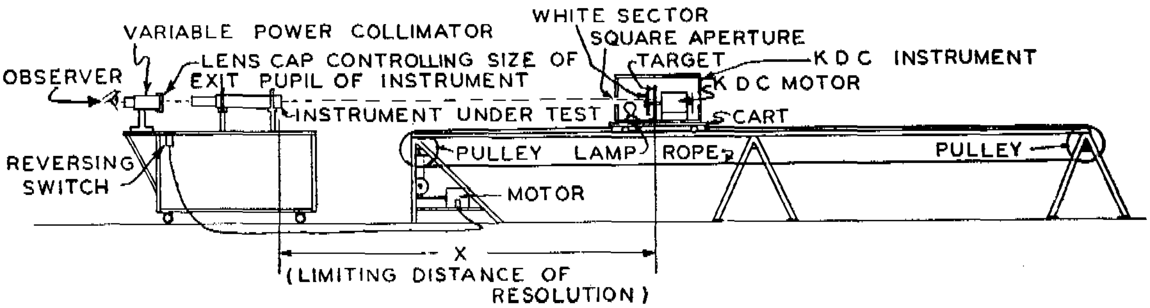
If such a chart is observed through a telescope as the distance from the observer to the chart is varied, a certain distance will be found beyond which the directions of the lines on the chart cannot be determined even though the magnification is such as to give an image of sufficient apparent size to permit easy examination. The critical distance depends on just two factors, the limiting aperture of the system, including the eye, and the optical quality. The latter is the factor which we desire to measure.

The Concept of KDC Efficiency

In the experiment just described, the chart would have to be moved to such a distance that the separations between the centers of the black lines would subtend an angle of approximately 4.5 sec of arc if the telescope were perfect and had an aperture of 1 in. If the target is observed with the unaided eye, and if the separation of the black bands were $\frac{1}{4}$ in. between centers, the chart would have to be placed at a distance of 50 ft, assuming a pupil diameter of 3 mm. If a perfect telescope is used as an optical aid, the distance is increased by the magnification of the telescope, provided the

pupil of the eye remains the limiting aperture of the system. If a 3-mm stop is placed on the entrance pupil of the perfect telescope, then the critical distance at which the target can be resolved is again about 50 ft in spite of the fact that the image received by the eye is many times the angular size that it was when the eye was used without aid. If the telescope is not perfect, i.e., if it contains defective parts, is improperly constructed, or is of such design as to ing aperture and any increase in the aperture of the telescope will result in a decrease in the critical distance, and thus the efficiency will be reduced.

To overcome this effect in the testing of optical instruments designed to utilize the pupil of the eye as the limiting aperture, auxiliary magnification is often employed. Such magnification has an additional advantage in that it increases the size of the image and thus reduces eye-



PROCEDURE:

(1) USING THE COLLIMATOR ALONE WITH SUFFICIENT MAGNIFICATION TO MAKE THE OBSERVATION OF THE TARGET COMFORTABLE, DETERMINE LIMITING DISTANCE OF RESOLUTION, X_c, USING A COLLIMATOR APERTURE EQUAL TO THE EXIT PUPIL OF THE INSTRUMENT TO BE INSPECTED

(2) DETERMINE THE DISTANCE OF LIMITING RESOLUTION, X_{c+i}, FOR THE COLLIMATOR AND THE INSTRUMENT UNDER TEST AS A UNIT USING THE SAME MAGNIFICATION FOR THE COLLIMATOR AS IN (1)

(3) THE EFFICIENCY, E, IS DEFINED BY THE FOLLOWING EQUATION:

$$E = \frac{100\, X_{c+i}}{M\, X_c}\ \%$$

WHERE M IS THE MAGNIFICATION OF THE INSTRUMENT UNDER TEST

FIGURE 20. Schematic diagram of KDC inspection apparatus.

have aberrations, the distance at which the target can just be resolved is considerably less. For example, it might be 40 ft. The ratio of these two distances is a convenient measure of the effects of the defects. In this case the efficiency would be given as 80 per cent. If the aperture of the telescope is increased from its previous value of 3 mm, but if the optics are so arranged as to insure that the entrance pupil of the instrument is still the limiting aperture of the system, the distances (for the perfect and imperfect instruments) will be increased proportionately, and if no additional defects were introduced by the utilization of the larger portion of the lenses, the percentage ratio will remain the same. At some point, however, the pupil of the eye will once more become the limit-strain. Depending upon the purpose of the test, in a way which will later be described, the auxiliary telescope may contain at its objective an aperture whose size is equivalent to the size of the pupil of the eye for an observer under the conditions normal to the projected use of the telescope.

MODEL 2-B KDC APPARATUS

The Model 2-B KDC apparatus consists of a substantial mounting for the telescope to be tested, an auxiliary telescope mounted between the eyepiece of the test instrument and the observer's eye, a long track parallel to the optical axis of the machine, and a target box mounted on a car running on this track. Figure 20 illustrates the physical arrangement of the parts.

The auxiliary telescope has a $1\frac{1}{4}$-in. aperture and a 5-in. focal length. A variety of eyepieces provides a wide range of magnification. As a result of experience, $50\times$ for each inch of entrance pupil of the instrument being tested is satisfactory for comfortable observation. Such a magnification provides an apparent angle of separation between the centers of dark bands of about 4 min to the eye of the observer. For any practical size of instrument under test, this magnification insures that the final exit pupil is of extremely small size. The support for the telescope to be tested consists of a pair of Y brackets, each constructed so as to be conveniently adjustable in height and horizontal position. The track is of lightweight construction and is about 50 ft long. The car supporting the target box is moved along the track by means of a motor-driven belt and pulley arrangement. The motor is under the control of the operator so that as he peers into the eyepiece he may move the target along the track until he has determined the critical distance. The target box contains, beside the target, a pair of light bulbs which may be adjusted to illuminate the target uniformly. In addition, a segmented white disk may be rotated in front of the target to control the contrast to permit a study of the effect of target contrast on efficiency. Figure 21 is a view of a typical target box.

This apparatus has been found to be of considerable use in testing optical instruments. It is simple to use, and requires neither a high degree of experience nor skill. A drawback is that it requires considerable space for the track, which is approximately 60 ft long. An undesirable feature is that it uses the telescope under test conditions at short object distances whereas most instruments designed for military purposes are intended for use with objects sensibly at infinity.

The Model 4 KDC Apparatus

Because of the space requirement of the Model 2 KDC apparatus, a new type, the Model 4, has been developed. This instrument is of table length, adequately satisfying the space requirement for convenient testing. The two new features of the design are the optical target which is produced by optical reduction, and the effective removal of the target to a large distance by collimation. The Figures 22 and 23 show the Model 4 KDC apparatus. The diagram, Figure 24, illustrates the arrangement of the optical parts to provide the effect of motion within a short space. In the lower right corner of Figure 24 is a target, modified from a Bureau of Standards Foucault test chart, of the type used in this apparatus.

FIGURE 21. The target box of Model 2 KDC apparatus.

The target is illuminated by two 40-w lamps at a distance of about 2 in. The bulbs and target are surrounded on the front and sides by a metal screen to keep direct light from reaching and disturbing the observer. The collimating unit consists of a tube with the collimating objective at one end and a microscope objective at the other. The microscope objective forms a greatly reduced image of the target inside the tube. Motion of the target toward or away from the microscope objective produces a much smaller motion of the image in the tube and at the same time a change in size of the target image. Looking into the collimator objective, the changes in apparent size of the target are equivalent to moving the target on the track of the Model 2 instrument.

The collimating objective has a diameter of

[redacted]

3 in. and a focal length of 15.75 in. The lens has been hand-corrected and interferometer-checked for high quality. Since the target distance for optimum performance is usually stated in the specifications for the particular instrument to be tested, a method must be employed to adjust the collimation for this distance. A telescope of high quality is focused on this purpose, a perfect instrument consisting of a very carefully figured objective and eyepiece. It is always used with an aperture stop equal to the entrance pupil of the instrument to be tested. The purpose of this telescope, in addition to being an aid in adjustment as described, is to act as a basis of comparison in that the limiting distance of resolution for a

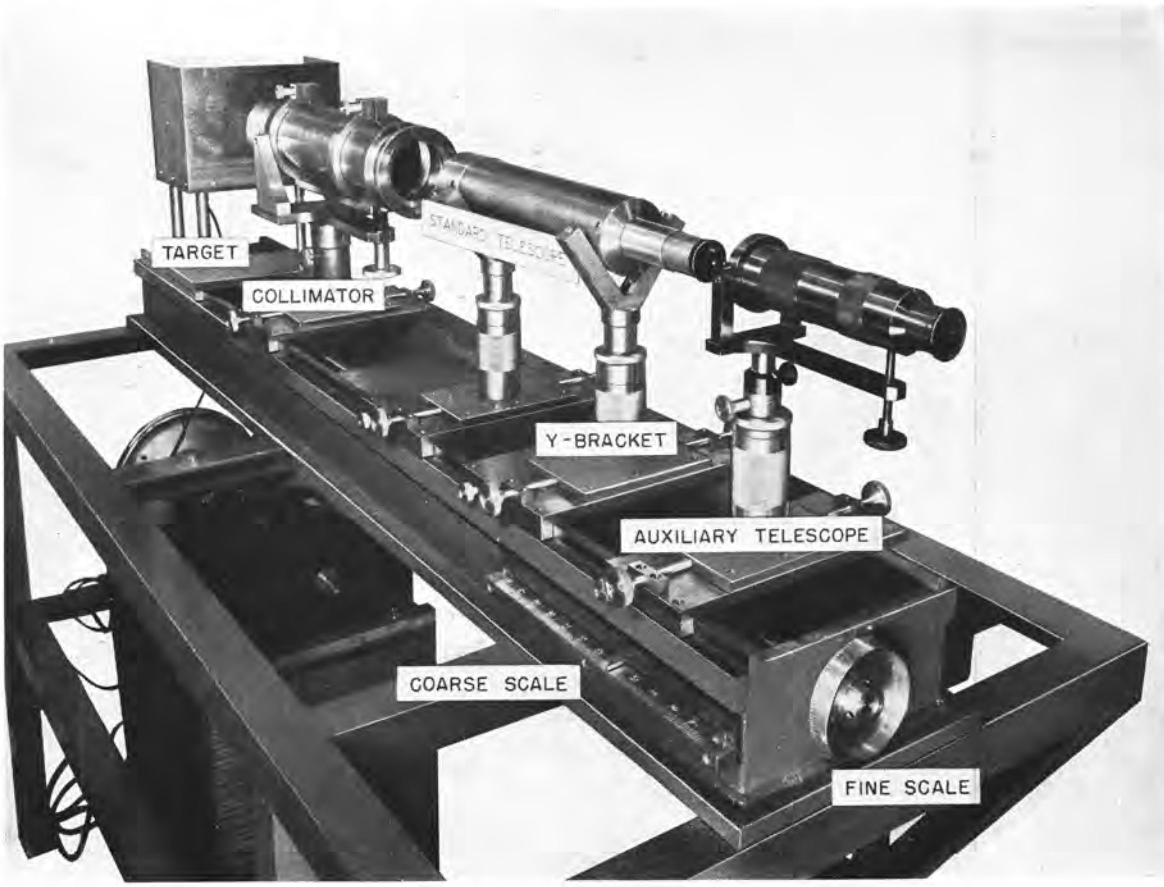


FIGURE 22. The Model 4 KDC apparatus with standard telescope in place.

a target at the specified distance, and is then placed in the KDC machine and used to adjust the collimator so that the test target is in sharp focus. The focusing is accomplished by changing the distance between the collimator and microscope rather than the distance between the microscope objective and the real target. After the adjustment for target distance, the real target may be moved to obtain the critical position for resolution.

The standard telescope just mentioned is, for perfect instrument may be established with it. It is to be pointed out here that the spacing of the real target and the focal length of the microscope objective are so chosen as to make the setting of the real target for the critical distance for the perfect instrument correspond to a virtual target distance equal to that specified for the instrument to be tested.

An auxiliary telescope is employed to produce enough overall magnification so as to reduce the exit pupil below the minimum diameter of

[redacted]

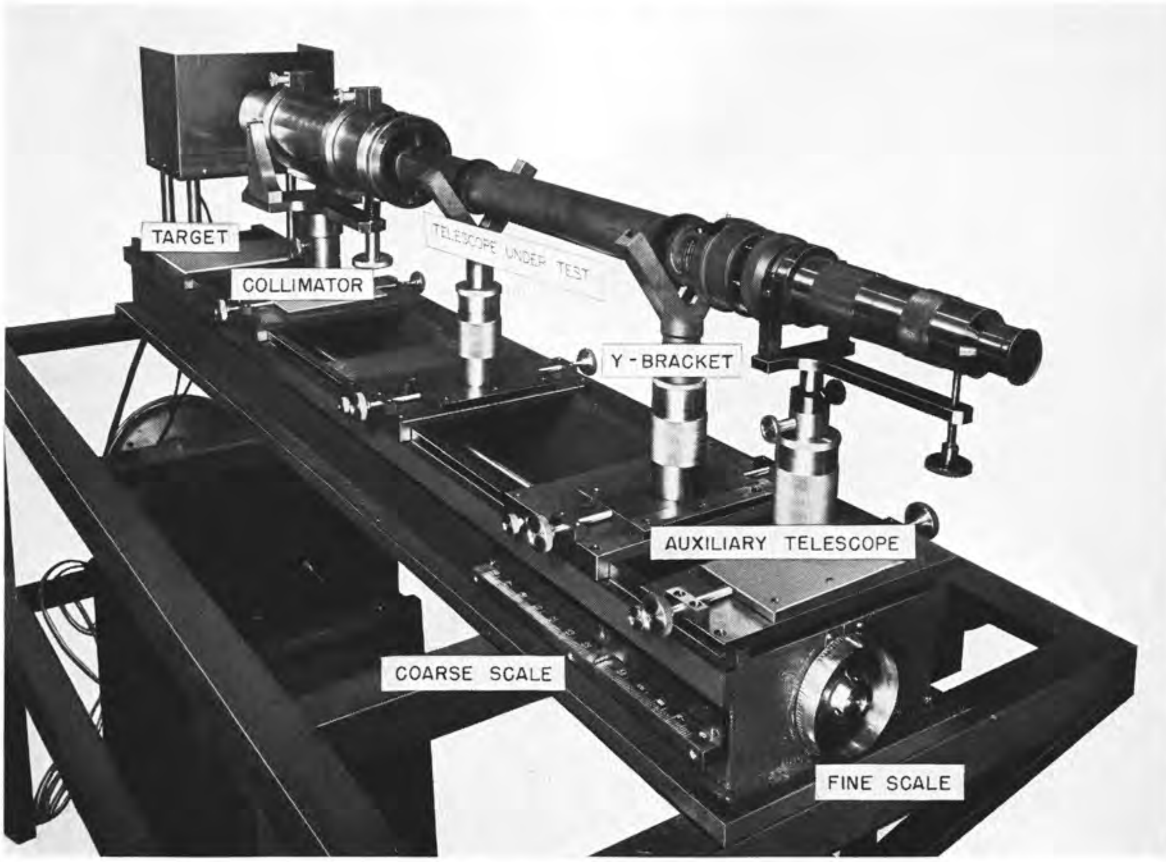


FIGURE 23. The Model 4 KDC apparatus with production telescope under test.

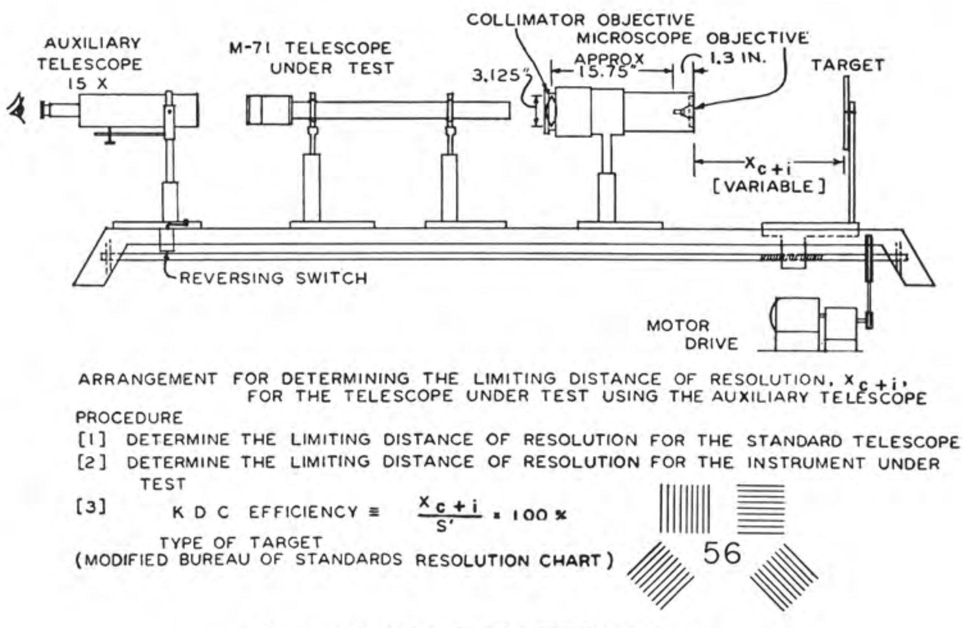


FIGURE 24. The Model 4 KDC apparatus.

the pupil of the eye. Thus, the resolution of the eye is removed from the measurements to a very great extent. The objective of the auxiliary telescope is equipped with an entrance stop. This stop may correspond to the diameter of the pupil of the average observer's eye, or to the specified exit pupil of the telescope to be tested. The auxiliary telescope produces enough magnification to enlarge the apparent target to a comfortable size and thus reduce eyestrain.

The mechanism for controlling the apparent target distance consists of a screw and slide arrangement which moves the real target with respect to the microscope objective. The position of the target along the slide is indicated on a scale convenient to the observer. The machine is so constructed as to provide a motion of the target from a distance of 6 in. to 16 in. from the microscope objective. This range has proved adequate for testing a wide variety of optical instruments.

The motion of the real target produces some motion of the image at the focus of the microscope objective, but this motion is small compared to the depth of focus of the collimator objective. The principal result is the change of size of the image of the target. The net effect is to produce a target at a nearly fixed apparent distance but with variable line spacing.

With the Model 4 KDC apparatus, the concept of efficiency is based upon the real position of the target. If the scale reading for a distance corresponding to the limit of resolution of the standard telescope is S, and the distance for the telescope under test is X, the efficiency E is

$$E = \frac{X}{S} \times 100 \text{ per cent.}$$

This relation depends upon the fact that the size of the image formed by the microscope objective is inversely proportional to the target distance over the range of distances employed. The zero of the scale corresponds to the case in which the target is coincident with the microscope objective.

Procedure for Making a KDC Determination

The Model 4 KDC apparatus, because of its convenient size and constant object distance, has replaced the Model 2 for production control. The procedure for carrying out a test on this machine is as follows:

1. The alignment is checked by means of gauges described later in this section.
2. The standard telescope is focused on an object at the required object distance for the instrument to be tested.
3. The standard telescope is placed in the KDC apparatus. The Y supports are adjusted to bring the axis of the telescope into line with the axis of the collimator, and the collimator is focused to bring the target into sharp focus. It is generally convenient to run the target carriage in to a distance of about 7 in. so that the number in the center of the array is well resolved. (See Figure 24.) This adjustment is made without changing the focus of the telescope from that of step (2).
4. Next, the auxiliary telescope is placed in the machine and focused to bring the numeral on the target into sharp focus.
5. With the auxiliary and standard telescopes in position, the target distance is increased until the observer can no longer determine the direction of the parallel lines in any one of the various groups of the target. During the measurement, the objective of the standard telescope is stopped with an aperture equal to the entrance pupil of the telescope to be tested.
6. The reading of the scale at this position gives the value S in the equation above.
7. The standard telescope is replaced by the one to be tested. It may be necessary to readjust the Y supports to align the axis of this telescope to that of the collimator.
8. The target is run in to about 7 in. and the telescope under test is focused to bring the number on the target into sharp focus.
9. The target is then moved away until the critical distance of resolution is reached. The criterion is the same as in step (5).
10. The reading of the scale gives the value of X, and the efficiency E is, as before,

$$E = \frac{X}{S} \times 100 \text{ per cent.}$$

When testing a large number of identical instruments, steps (1) through (7) need be made only once when the KDC machine is first placed in operation. Steps (8), (9), and (10) are all

that are required for each new test telescope.

Two gauges are provided with the instrument to aid in the adjustment in step (1). In order to adjust properly the distance between the target and the microscope objective, a space gauge is used. Figure 25 shows this gauge in position. The principal plane of the microscope objective is 2.30 in. inside the collimator, measured from the end of the tube. It is convenient to set the scale reading at 7.0 in. The required distance from the end of the collimator tube to the target is then 7.00 − 2.30 = 5.70 in. The U-shaped gauge is thus 5.70 in. between outside ends. With the indicator set at 7.00 and the gauge in place, as shown in Figure 25, the collimator is moved along the base until its end contacts the gauge.

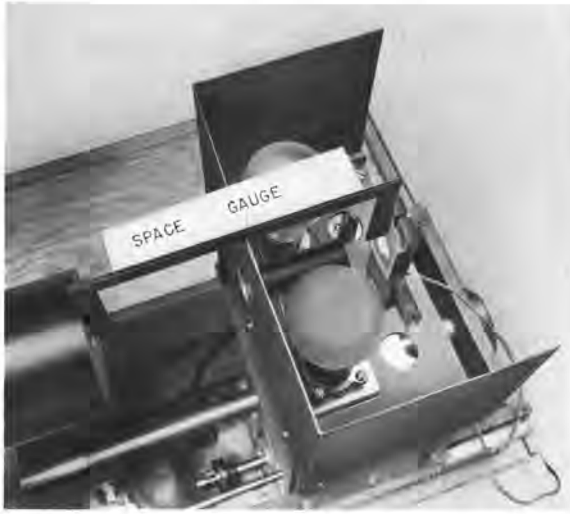


FIGURE 25. The target of the Model 4 KDC apparatus with space gauge in position.

The second gauge is used to make the proper alignment of the optical parts of the KDC apparatus. This gauge, called the alignment gauge, is composed of two parts, a base which fits the ways on the optical bench and supports a circular plate, and a pointer which may be screwed into the center of the plate. Figure 26 shows the gauge with the pointer in place. The center of the target, when coincident with the end of the pointer, is then on the optical axis of the machine. Slots under the fastening screws supporting the target permit horizontal and vertical motion. The face of the gauge with the pointer removed is used to check the alignment of the collimator, and when the circular plate is concentric and in contact with the cell of the objective, the positioning is correct. The alignment gauge and the positioning screws of the collimator are shown clearly in Figure 27.

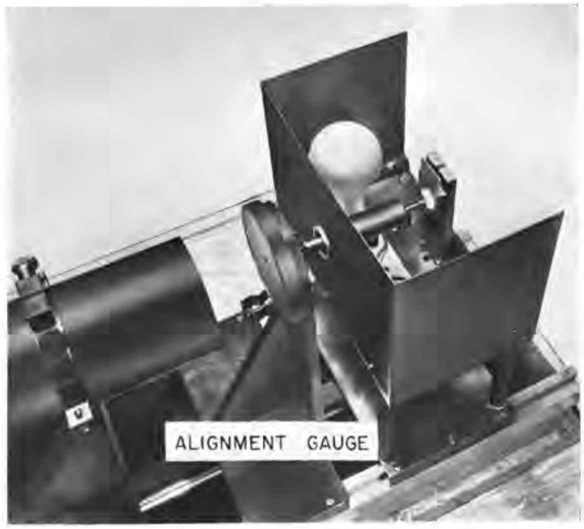


FIGURE 26. The alignment gauge in position for centering the target.

SPECIAL FIXTURES AND ATTACHMENTS FOR KDC APPARATUS

The KDC apparatus may be used not only to determine the resolving power of an instrument on its axis but off axis as well. Certain fixtures and attachments have been developed for the purpose of making these off-axis measurements. Besides those designed to support tank sights (M-70, M-71, M-72, M-76, and others), a special support for binoculars makes the measurement of these instruments easy.

Two different types of off-axis fixtures are available. In one type, Models 1 and 2, the telescope being tested and the auxiliary telescope are mounted on pivoted supports so that the test telescope may be rotated about its entrance pupil and the auxiliary telescope about the test telescope's exit pupil. Figure 28 is a diagram showing the relation of the various angles of rotation. A similar fixture for use with binoculars is illustrated in Figures 29 and 30.

A different type of off-axis fixture employs four front surface mirrors, two fixed and two

rotatable. Figure 31 shows the optics of the fixture. A typical setup may be seen in Figure 60. The camera shown in the figure is replaced by the normal auxiliary telescope for KDC efficiency measurements.

TABLE 5. A comparison of KDC efficiency values for tank telescopes determined by the Model 2 and the Model 4 KDC apparatuses.

M-70 telescopes serial nos.	Axial KDC efficiency (per cent) Model 2	Model 4
57228	63	60
57109	82	84
57098	65	63
57194	61	65
57104	94	92
54695	91	90
54532	63	63
58598	73	72
57209	80	80
57105	63	65

In order to determine the relative accuracy of the Model 4 KDC apparatus with respect to Model 2, a large number of telescopes have been

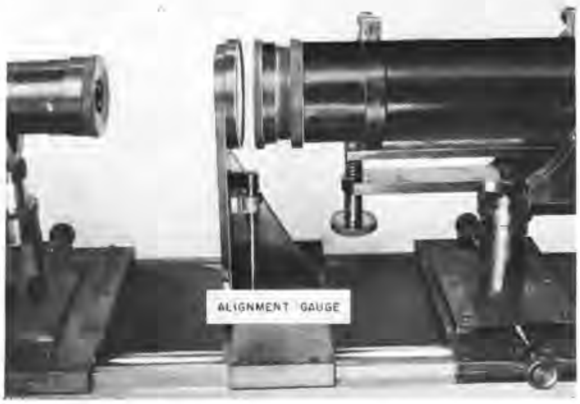


FIGURE 27. The alignment gauge in position for squaring the collimator.

measured by both machines. Table 5 shows the results for a typical set of ten M-70 telescopes. It will be noted that not only are the poor telescopes poor on both machines and the good ones likewise good, but the actual values of the efficiencies are in all cases very close together. This table also shows the range of efficiencies observed in a single type of telescope. Five telescopes have efficiencies less than 70 per cent, whereas two have efficiencies greater than 90 per cent. These telescopes were not selected in any special way, and may be considered as samples of production. This telescope obviously has a potential efficiency of something better than 90 per cent, yet half the standard production models in this group fall below 70 per cent. Table 6 shows a comparison between the KDC efficiency values and a group of values obtained by visual grading of tank telescopes.

TABLE 6. Comparison of KDC efficiency with visual grading.

Instrument no.	Exit pupil	Observer 1	2	3	4	KDC efficiency (per cent)
4553	7	2	2	2		72
4468	7	1	1	1		88
4553	2.5	2	2	2		90
4468	2.5	1	1	1		97
4524	7	2	2	2		68
4820	7	1	1	1		80
4501	7	2	2	2		77
4820	7	1	1	1		80
4501	2.5	1	1	1		98
4820	2.5	2	2	2		92
4980	7	1	1	1	1	95
2763	7	2	2	2	2	83
10628	7	4	3	3	3	82
2	7	3	4	4	4	60

TYPICAL RESULTS

Because of the great number of measurements which have been made on various optical instruments with the KDC apparatus, no attempt will be made here to present the laboratory results in detail. Sufficient laboratory observations have been made, however, to lead to the acceptance of the machine as a control of production for the Type M-71 tank telescope and there are good indications that its use will continue to grow for other types of instruments.

One question that naturally arises concerns the degree of correlation between the visual grading of a telescope and the KDC efficiency. A group of telescopes were graded in pairs, each observer deciding independently which one of the pair was the better. Some of the grading was done on a bright clear day using a distant landscape, while some of the grading was done with an illuminated target indoors in a dark room. A few of the telescopes were graded twice, once with a 7-mm exit pupil and once

with a 2.5-mm pupil stop. The results of the grading and the measured values of the KDC efficiency appear in Table 6.

Besides the nearly perfect correlation evidenced in the table between visual grading and order at 2.5 mm. The KDC efficiencies show the same result. In all cases the efficiencies improved with reduction of aperture, indicating some residual spherical or chromatic aberration in the design.

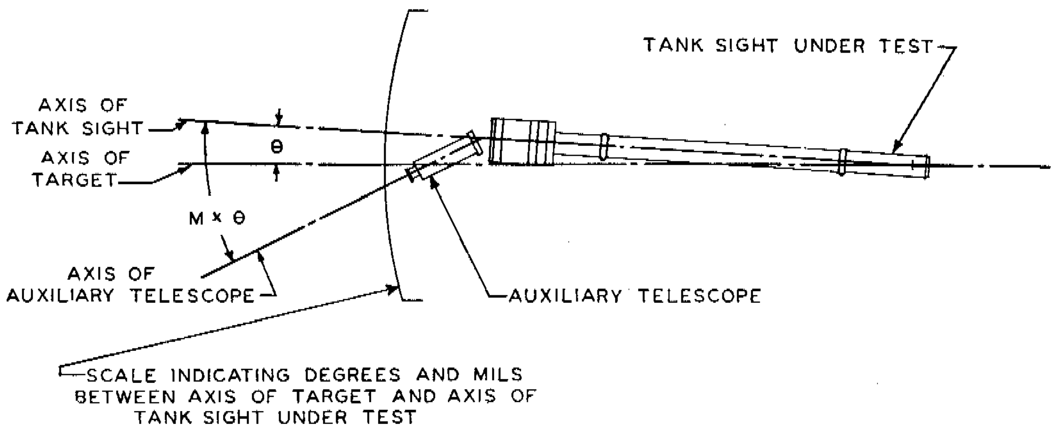


FIGURE 28. The off-axis fixture for tank sights.

KDC measurements, several other points are of interest. In the case of the fourth pair, the efficiencies are quite close together (77 to 80 per cent) yet the observers could detect a difference in the performance. The present specification on the type of telescope represented in all but the last group is 75 per cent minimum. As a basis of comparison, 92 to 94 per cent efficiencies at full aperture appear possible with the design. The pair 4501-4820 was graded in one order at 7-mm exit pupil and in the reverse

Another interesting result appears in Table 7 which summarizes the KDC efficiencies of 20 M-70D telescopes of each of five manufacturers. Manufacturer No. 1 has his production under such control that nearly every telescope is 90 per cent or better. On the other hand, manufacturers No. 4 and No. 5 have trouble making any as good as this. Five telescopes manufactured by No. 1 measure 100 per cent and six measure 99 per cent. As a matter of fact, one made by No. 4 measures 99 per cent and one

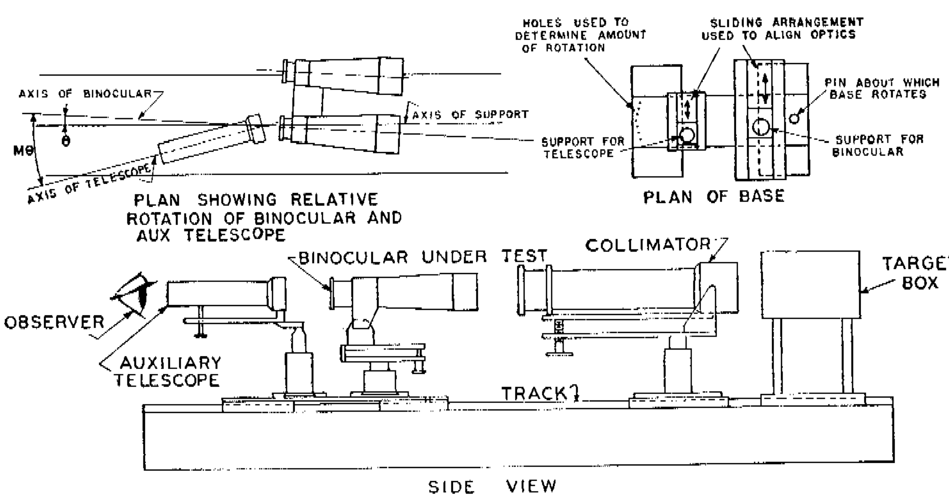


FIGURE 29. The off-axis fixture for binoculars.

each made by Nos. 4 and 5 measure 97 per cent, so it is quite possible by the methods used by all manufacturers to produce telescopes with efficiencies of 97 per cent or better. If the specifications were set at 80 per cent or better, 37 per cent of the one hundred samples would be rejected yet all of manufacturer No. 1 would be accepted. Obviously better production methods are required in the case of Nos. 3, 4, and 5.

FIGURE 30. The off-axis fixture for binoculars.

TABLE 7. KDC efficiencies (per cent) of M-70D telescopes.

Manufacturer	100-90	89-80	79-70	69-60	59-0	Total
1	19	1	0	0	0	20
2	11	5	3	1	0	20
3	1	12	7	0	0	20
4	2	3	8	4	3	20
5	2	2	7	7	2	20
Total	35	23	25	12	5	100

The telescopes discussed above were measured not only on the axis, for which the results are shown in Table 7, but also at a number of positions off axis. Twenty, forty, and sixty mils to right and left were chosen as standard values of the angle of view. Figures 32 and 33 show the results for manufacturers Nos. 1 and 5 respectively.[9] The general shape of the curve relating KDC efficiency and field angle for a tank telescope is well illustrated in these figures. Off axis the efficiency drops, due to aberrations, particularly coma and astigmatism.

Table 8 shows the results from KDC measurements for a group of 7x50 binoculars. The measurements on two captured binoculars are also included for comparison. The Japanese binocular had an unusually high efficiency for an instrument of its power and aperture. It should be noted that if the acceptable KDC efficiency is placed at 80 per cent, while nine of the twenty optical systems would have passed, only two complete binoculars would be accepted. Binocular No. 1 includes the second best (left) and the worst (right) of the twenty optical systems. Eighty per cent is probably too high a

[redacted]

requirement for this system. Seventy per cent may be adequate and more practical, but 90 to 92 per cent can obviously be attained with this design.

One other laboratory result is of special interest. A simple telescope was deliberately defaced by scratching the objective. A far greater effect was produced by scratches on the front surface of the field lens of the eyepiece. The telescope had originally a KDC efficiency of 100 per cent. When the field lens had 25 per cent of its surface scratched, the efficiency was 95 per cent for a target contrast of 100 per cent, and an efficiency of 87 per cent for a contrast of 20 per cent. Thus scratches have very little effect upon the performance.

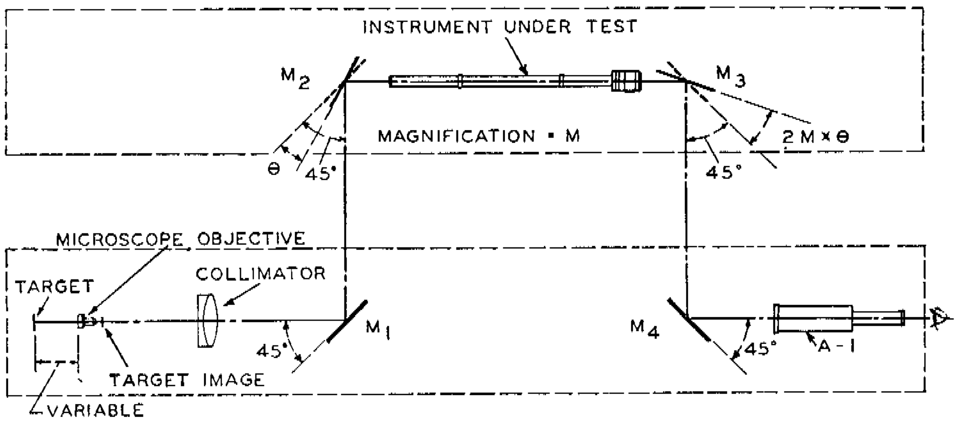


FIGURE 31. The four-mirror off-axis fixture.

TABLE 8. KDC efficiency of ten 7x50 binoculars (per cent).

No.	Left barrel	Right barrel
1	91	62
2	79	76
3	78	76
4	78	73
5	83	86
6	85	76
7	81	73
8	72	81
9	76	87
10	92	87
Best	92	87
Average	81	78
Worst	72	62
German (8x40)	92	89
Japanese (14.7x88)	Broken	96

THE PRECISION OF THE KDC APPARATUS

As is usually the case in other kinds of physical measurements, the precision of the results obtained with the KDC apparatus depends on many factors. Some of the most important of these factors will be considered individually in what follows. One of the most obvious effects to be expected is a possible relation between KDC efficiency and target illumination. The illumination may be varied by changing the bulbs in the target box. Those actually used ranged from 10 w to 100 w, two of the same size always being employed. The results appear in Table 9. The illumination in watts is the sum of the two bulbs, the illumination in foot-candles is the actual light on the target, X is the limiting distance of resolution, and S is computed for the limiting distance for the eye times the magnification of the instrument. The trend of resolution is toward larger distances for higher light intensities, both with the instrument and with the standard. The efficiencies remain nearly the same, however. It thus appears that

TABLE 9. The effect of target illumination on KDC efficiency. Model 2 apparatus.

Footcandles on target	X	S	Efficiency
40	35.5	36.4	97.6
50	36.5	37.3	97.8
115	36.9	37.9	97.4
200	37.8	38.5	97.3
400	38.1	39.1	97.6
800	38.2	39.6	97.8

the result is sensibly independent of the level of illumination. This being the case, the choice of illumination may be based upon ease of measurement. Two 40-w lamps are normally used to give a level of about 200 footcandles at the target.

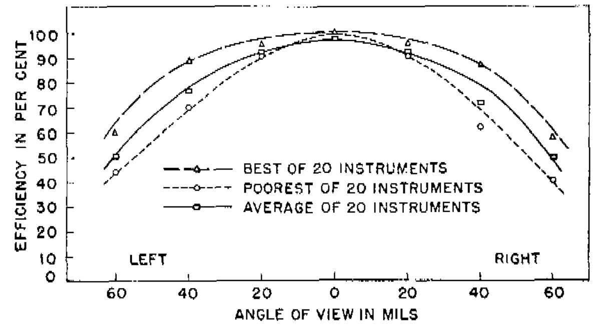


FIGURE 32. KDC efficiency vs angle of view for manufacturer No. 1.

If the KDC efficiency is to be a true property of the telescope under test and is not to depend on the way in which it is measured, it must be demonstrated that the value is independent of auxiliary magnification. The effect of magnification is clearly shown in Table 10. For large values of contrast, the only ones used in practice, the limiting distance increases rapidly with the magnification. At some value near 30× overall, the resolution becomes constant and further magnification does not increase it. At the value 30×, the limit of resolution of the system is that of the telescope under test and not that of the eye. On this basis a standard value of about 50× overall is generally used. An auxiliary telescope is chosen to raise the magnification of the instrument being tested to this amount.

One other point in this connection has been investigated, namely, the relation of target size and number of lines to target distance for limiting resolution. Figures 34 and 35 show the observed relations. From these results it is safe to assume that a telescope whose KDC efficiency is determined on an instrument with a target having one size and number of lines will be nearly the same when determined on an instrument with a different target. Further, for a telescope whose efficiency is 100 per cent the angle of minimum resolution for parallel lines will lie between 4.62 and 4.70 sec of arc per inch of aperture. The carefully built standard S-1 is assumed to be 100 per cent efficient.

The probable error of a single KDC efficiency determination depends on the auxiliary magnification and the value of the efficiency of the instrument. The effect of target contrast has already been discussed and since all production measurements are made with contrasts of 100 per cent only the results for this value will be discussed.

TABLE 10. Effect of magnification on resolution. (Angle of minimum resolution for M-76C telescope, aperture 0.863 in.)

Total magnification	100%	50%	30%	10%
		($\times 10^{-5}$ Rad)		
7.5	5.2	5.5	7.0	9.0
10	4.0	4.6	5.0	8.2
15	3.3	3.9	4.3	7.5
20	3.05	3.6	3.9	7.2
30	2.86	3.35	3.62	7.2
40	2.85	3.28	3.60	7.7
50	2.85	3.25	3.60	8.5
60	2.84	3.27	3.64	9.2
70	2.85	3.30	3.67	10.0

Many measurements have been made with Model 2 KDC apparatus and some with the Model 4, for the particular purpose of determining the precision of a single efficiency measurement. Seven different observers were in-

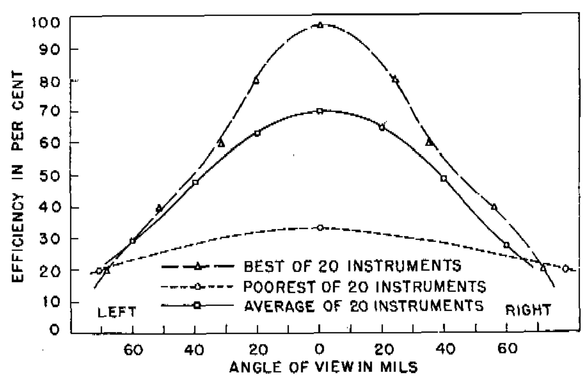


FIGURE 33. KDC efficiency vs angle of view for manufacturer No. 5.

volved in these measurements, six on the Model 2 machine, two of these and a third new observer on the Model 4 machine. Tables 11 and 12 exhibit the results of this set of measurements. It is to be noted that some observed values of the efficiency are means derived from

[redacted]

25 observations, and some from 50, but a majority are means of 100 observations. All of the probable errors indicated in the tables were deduced from the agreements of the individual measurements on the assumption that the errors were distributed at random. The numbers which appear in the tables are the probable server, appears in the tables. Associated with this value of efficiency is a probable error of a single observation deduced from the residuals within each group. The residuals were computed from the mean for that group. In the column headed, "Means," the efficiencies are the simple unweighted means for each group of six.

TABLE 11. The probable error of a single KDC efficiency measurement.

Model 2

Telescope	Observer 1*	2*	3*	4†	5†	6*	Means	Most probable values
M-71 No. 2335	84.4 ±0.65	84.7 ±0.68	84.5 ±0.45	82.0 ±0.69	83.0 ±0.49	84.9 ±1.07	83.9 ±0.69	84.3 ±0.59
M-72 No. 12242	59.3 ±0.90	58.3 ±0.90	59.5 ±0.60	58.5 ±0.77	56.1 ±0.49	61.2 ±0.96	58.8 ±0.77	58.6 ±1.06
M-76 No. 5492	74.4 ±0.92	72.9 ±1.35	71.5 ±0.66	76.6 ±1.13	76.4 ±0.64	74.4 ±1.75	74.9 ±1.07	73.7 ±1.36
S-3	97.5 ±0.24	96.6 ±0.92	97.7 ±0.38	99.4 ±0.66	97.0 ±0.52	99.4 ±0.96	98.0 ±0.61	97.5 ±0.38
PE	±0.68	±0.96	±0.50	±0.81	±0.53	±1.18	...	...
SE	+0.04	−0.38	−0.03	+0.22	−0.79	+1.64	...	±0.85

* 100 observations.
† 50 observations.

errors of single observations and are not to be confused with the normally reported probable errors of a mean.

The efficiencies for one or more examples of three different types of telescopes appear in the tables. On the Model 2 apparatus, each tele- The probable errors in this column are the means of the probable errors for each observer. The column headed, "Most probable values" contains the means, weighted according to the number of observations and according to the probable error for each group. The probable

TABLE 12. The probable error of a single KDC efficiency measurement.

Model 4

Telescope	Observer 1*	2†	7‡	Means	Most probable values
M-71 No. 9911	79.5 ±0.45	74.7 ±0.63	78.5 ±0.95	77.6 ±0.68	76.6 ±1.05
No. 2342	74.7 ±0.79	84.1 ±3.48	82.3 ±0.95	80.4 ±1.73	79.7 ±2.58
No. 2337	84.1 ±0.79	85.0 ±1.35	81.3 ±1.03	83.3 ±1.06	83.4 ±1.08
No. 2335	84.1 ±0.32	86.9 ±1.11	86.9 ±2.22	86.0 ±1.22	84.7 ±0.83
M-72 No. 2	75.9 ±1.38	69.7 ±0.66	75.9 ±1.78	73.7 ±1.27	70.4 ±1.30
No. 12242	64.4 ±0.53	61.3 ±0.72	66.6 ±1.05	64.2 ±0.76	62.8 ±1.34
No. 12305	60.4 ±0.39	58.9 ±0.72	59.6 ±1.05	59.7 ±0.72	59.6 ±0.47
M-76 No. 4980	97.9 ±0.18	95.8 ±0.18	96.9 ±0.81	96.8 ±0.39	96.4 ±0.57
PE	±0.60	±1.11	±1.23	...	±1.15
SE	+0.84	−0.58	+0.91	...	...
		+0.50			

* 25 observations.
† 100 observations.
‡ 50 observations.

scope, one of each type, was measured independently 50 or more times by six observers. Four of the observers made 100 measurements on each telescope; the other two made 50. The mean value for each group of 50 or 100 measurements, for each telescope and for each ob- error of the most probable value referred to unit weight is also given in this column. The latter includes the probable errors of a single observation deduced from each observer's probable error, as well as the agreement of each observer's mean with the most probable value.

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Across the bottom of the group of observations on the Model 2 machine is a row labeled "PE." These numbers are the mean values of the probable errors for each observer. The row headed "SE" contains the systematic errors deduced from the agreement of each observer's mean

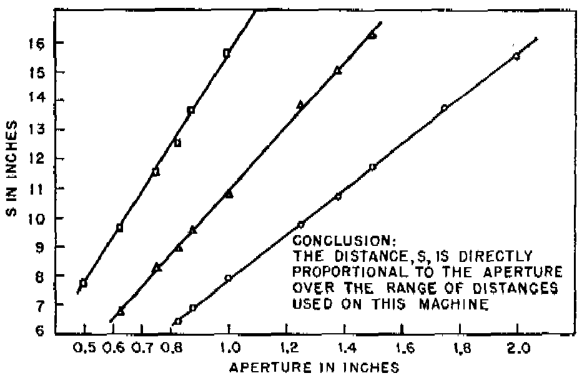

FIGURE 34. The limiting distance of resolution vs aperture.

with the most probable value. The measurements for the Model 4 machine follow the same system except that more than one example of two of the telescope types was measured.

A number of facts concerning the expected accuracy of a single observation on the KDC machine may be deduced from Tables 11 and 12. First and probably most important is that for any telescope picked at random and for any observer picked at random, the probable error to be expected from a single observation is about 0.85 per cent for the Model 2 machine and 1.15 per cent for the Model 4 machine. The probable error here means that for an observation made by an observer, half the time the value which that observer obtains will have a residual from the correct value equal to or less than the reported probable error. The remaining half the time the value will be equal to or greater than the reported probable error. By the correct value is meant the weighted mean of a very large number of observations made by a very large number and variety of observers on the particular telescope in question and on the particular model of the KDC machine employed. A survey of the most probable values of efficiency and their probable errors shows little correlation between these two numbers. There is some evidence to indicate that higher values of efficiency may be determined with higher precision, but in the range from 60 per cent to 80 per cent the probable error does not change significantly.

There is considerable variation among observers. Consider for a moment a group which includes good and bad observers. Each individual of this group makes a large number of measurements on a particular telescope. The most probable value of the efficiency will be the weighted mean of the means of each individual's observations. The weights to be applied will depend upon the internal agreement in each individual's observation set. From the table we may deduce that those observers in this group who have large probable errors may be expected to have large systematic errors also. For example, observers Nos. 6 and 7 have the largest probable errors and they also have the largest systematic errors. Observers Nos. 1 and 3 on the other hand have small probable errors and very small systematic errors. Observer No. 2 is quite erratic. In one case he had a probable error by far the largest of any in the entire group, but in another case he had a probable error equal to the smallest of any in the group. The mean value places him with the poorer observers and his systematic errors are fairly large. Observers Nos. 1 and 2 meas-

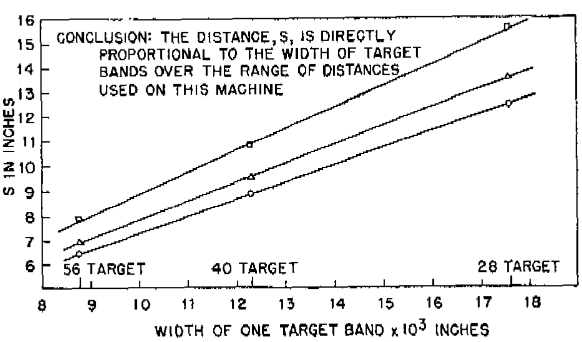

FIGURE 35. The limiting distance of resolution vs target bandwidth.

ured telescopes on both Model 2 and Model 4 KDC machines. Observer No. 1 was the better in both cases, observer No. 2 taking second place, both on the basis of probable errors and on the basis of systematic errors.

In two cases the same telescope was observed on both machines. In the case of telescope M-71,

[redacted]

No. 2335, Model 2 machine yielded a most probable value 0.4 per cent smaller than the Model 4 machine. This difference is of the same order as the probable error of a single observation. Since the most probable values depend in one case upon 450 observations and in the other case upon 175, it seems safe to say that there is actually a systematic difference of 0.4 per cent between the two machines for this value of efficiency. Telescope M-72, No. 12242, was also measured on both machines. The Model 2 machine yielded a value 4.6 per cent smaller than the Model 4 machine. This value is nearly four times the probable error of a single observation and some forty times the probable errors of the means. Thus in the neighborhood of 60 per cent efficiency it appears that the Model 4 machine gives a value 4.5 per cent higher than the Model 2.

All of the foregoing results depend on a very large number of measurements made by what appears to be a random sampling of observers. Thus the conclusions drawn from the treatment of the observations should be trustworthy. It is not known, however, whether the systematic differences between the two machines would be repeated on other machines of the same model, or whether they are peculiar to the particular instruments employed.

The Use of the KDC Apparatus for Inspection

The KDC apparatus may be used either for the inspection of completed telescopes to determine the degree to which the instrument meets its specifications, or for the evaluation of a particular optical design. So far in this chapter we have only been concerned with the first of these, and in this section will be given some recommendations for such use. In the next major section (see Section 4.4) are discussed some of the applications to design evaluation.

One of the primary requisites for an inspection procedure is that it be simple and rapid. It was thought at first that tests should be made on targets of reduced contrast since most targets viewed with military telescopes are of low contrast. The applicability of this assumption depends on the inspection philosophy. Experience has shown that if a telescope performs well at 100 per cent contrast it will perform well at all other contrasts; likewise a telescope which is poor at high-target contrast will be poor by comparison at low contrasts. In fact the spread between good and bad instruments will be larger at high contrasts than at low. Since the measurements are not only more precise at 100 per cent contrast but are also easier to make, it seems best to carry out tests at 100 per cent contrast, even though this does not represent the conditions of use. It is not the purpose of this test to determine how the telescope will perform in use, for that should have been tested before the design was adopted, but rather to grade individual instruments by means of those factors upon which its performance depends.

In a similar way the KDC efficiencies of an instrument for off-axis rays are very valuable and educational for the designer, but they yield no more information on the ability of the telescope to meet the specifications than does a single measurement on the axis. No telescopes have been found which are good on the axis and poor when off, or poor on and good off the axis, as compared to a normal telescope. Thus one measurement suffices.

The question of the size of the exit pupil to be employed during the measurements is of the same type. Under normal conditions of use, the exit pupil is limited to 7 mm or so by the pupil of the eye. Naturally the telescope behaves better at this reduced aperture than if it were used at full aperture. But since a good telescope at full aperture is also good, in a comparative sense, if the aperture is reduced, while a telescope which is poor at reduced aperture is still worse at full aperture, the test is most sensitive at full aperture. It is to be expected that the KDC efficiencies will be smaller than those deduced from the resolving power using the eye without auxiliary magnification. This is unimportant, however, since the poorest usable telescope will be selected by considerations other than a pre-established value of the efficiency. This telescope may then be tested at full aperture and the value so obtained embodied in the specifications.

It is therefore desirable that the specifications indicate the minimum KDC efficiency at

full aperture for a target of 100 per cent contrast on the axis. The acceptance test then consists of one simple measurement. If a telescope which has an efficiency equal to the minimum specification is just satisfactory in the service for which it was designed, then all telescopes with this or greater efficiency will be satisfactory and those with lower efficiency will not. Thus the purpose of the test is fulfilled.

4.3.2 The Michelson-Twyman Interferometer

In spite of the fact that the interferometer was first developed and used to measure the motion of the earth with respect to the ether, it has become a very valuable tool in many widely different fields. The use of this device, or the principle on which it is based, for the measurement of distances with extreme accuracy is well known. The underlying principle of the interferometer, that of portraying light path differences as dark bands across the field of the instrument, has become very useful for the testing of lenses, prisms, and even complete instruments.

F. Twyman has investigated the application of the interferometer to the study of optical systems in general. Others have developed methods for computing the shape and appearance of the interference fringes to be expected from known optical designs of lenses and simple combinations of lenses. This work has been used by the group at Pennsylvania State College with the aim of applying the interferometer to the inspection of optical components.

The problem is twofold. The instrument must be so modified as to be easily adjusted and used, for the interferometer is notable for its inherent difficulty of operation. The fringes for a perfect lens or other component must be computed or observed and the effect of errors determined so that an intelligent interpretation of the observed fringe pattern may be made in terms of the quality of the optical element.

The Principle of the Interferometer

The interferometer employs two light beams starting from a common source. After traveling over separate paths, these are recombined before entering the eye of the observer. Figure 36 shows the arrangement of the optical parts for a typical interferometer. The dividing plate *E* has a half-reflecting coat on the side facing the objective *D*. The collimated beam of light from *D* is split into two equal beams at this surface. One beam travels along the path *EFEJK* and to the observer's eye beyond *K*. *F* and *H* are fully reflecting mirrors. The other half of the beam proceeds along the path *EGHGEJK* and so to the eye.

When the beam is split at *E*, it is not divided geometrically, say into right and left or top and bottom halves, but each ray (all are parallel) is divided into two equal parts. Thus the cross sections of the two beams proceeding from *E* are equal and they recombine as they return to *E*. Let it be assumed as a first example that the distance which one half of each ray must travel is exactly equal to the distance which the other half of that ray travels. Then according to the wave theory of light, the two halves will arrive at *E* in phase and recombine into a ray exactly equal to the original ray from *D*, less the reflection and absorption losses of course. It is not necessary for each ray to travel a distance equal to the distance traveled by every other ray, provided the optical path lengths of the two halves of each ray are equal. The field of view as seen from *K* will then be of uniform intensity.

Now suppose that the mirror *F* is moved a short distance so that the path lengths for the two halves of each ray are different. The ray halves no longer arrive at *E* in phase and thus the illumination of the field of *J* is reduced. When the path lengths are different by one-half of a wavelength of the light used, the field will be completely dark.

Next assume that the mirror *F* is inclined so that along some line across this mirror the path lengths for the two ray halves are equal but at points on one side of the line the path length *EFE* is shorter than *EGHGE*, and on the other side *EFE* is larger than *EGHGE*. As the observer's attention moves across the field of *J*, he sees a bright band corresponding to the line on *F* where the path lengths are equal. On either side of this line the illumina-

tion decreases until the region is reached on F where the path length differs one-half a wavelength. Proceeding farther, additional bright bands correspond to path length differences of one, two, or any integral number of wavelengths.

It follows then that the interpretation of the light and dark bands which appear to an observer with his eye at K is simply one of path lengths. Taking any bright spot as an origin, any other bright spot in the field corresponds to a path length an integral number of wavelengths longer or shorter than the length at the origin. The dark bands show the regions which have path length differences equal to an integral odd number of half-wavelengths.

It must be remembered that the important factor is the optical path length and not the physical length. In a telescope it is desirable, even necessary, for good image formation that the optical path lengths from the object point to the image point be equal to within a small number of wavelengths.

The diagram previously referred to in Figure 36 shows an interferometer set up for the testing of prisms. Suppose the prism G is replaced by a perfect flat mirror, then the instrument may be adjusted to give a uniformly bright field, a uniformly dark field, or a number of straight parallel bright and dark bands. If now the mirror is replaced by a perfect prism, the mirror F must be moved away from E since the optical length in the other path is lengthened by the presence of the glass of the prism. Since the optical length in the perfect prism is the same for all rays, the original field as seen with the mirror alone may be again obtained. If the prism is imperfect in any way (faces not flat, or nonhomogeneous glass) the fringe system will so indicate. Figure 37 shows a set of interferograms of several prisms for an M-10 periscope. A number of different defects are shown. Views 7, 10, and 12 illustrate the nature of the fringe system when the prism contains striae. The other views are of prisms with imperfect surfaces. No. 8 is the most nearly perfect of this group, but the dark bands would be straight, parallel, and equally spaced if it were perfect.

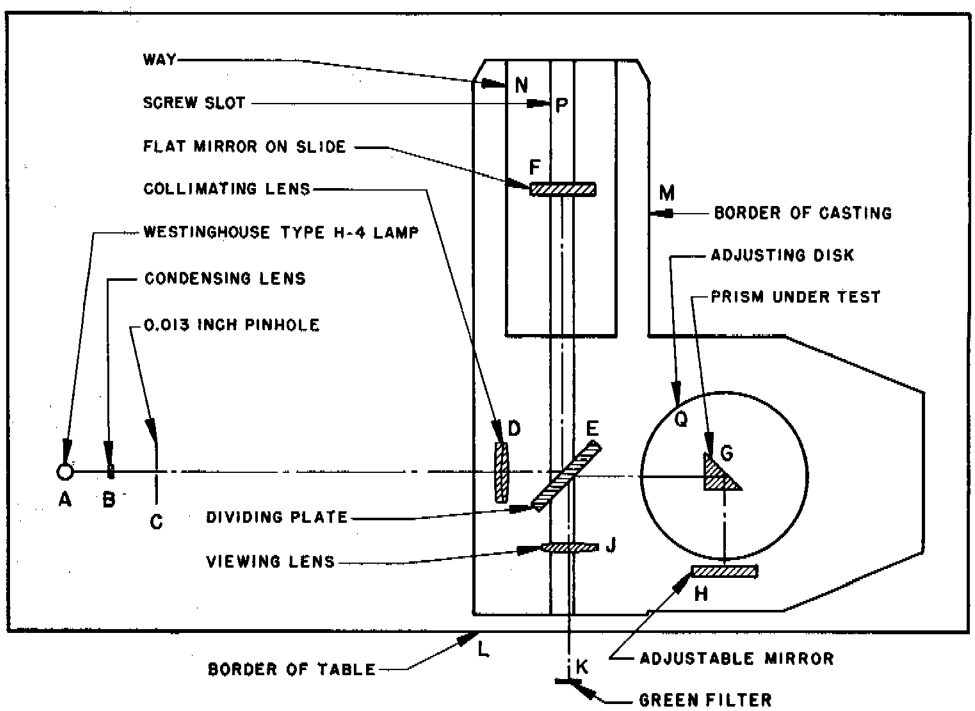

FIGURE 36. Diagram of I.1 Michelson-Twyman interferometer.

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4.3.3 The Pennsylvania State College I.1 Michelson-Twyman Interferometer

The basic parts of the I.1 interferometer are shown in Figures 38, 39, and 40. The light source is an H-4 Westinghouse mercury vapor lamp. It has been found that a 40-w lamp in series with the primary of the supply transformer improves the stability of operation. The light from the lamp is condensed on a pinhole which is at the focus of a collimating lens. This lens has an aperture of 2.5 in. and a focal length of 16.00 in.

The plane-parallel dividing plate of this instrument is aluminized on the face nearest the collimator. The aluminum coat is of such thickness as to reflect approximately 70 per cent of the incident light. The length of the adjustable light path is determined by the position of an optical flat aluminized on its first surface. This flat is mounted on a sliding carriage which is controlled by a screw and hand wheel convenient to the operator.

The upper surface of the casting, which forms the bed of the apparatus, is carefully machined to a flat surface. The front surface mirror in the second light path is mounted in an easily adjustable support which may be moved around over the surface of the casting. Between the mirror and the dividing plate is a rotating table upon which the optic to be tested is mounted. A simple double convex lens with an aperture of 2.4 in. and focal length of 7 in. is employed for viewing the field. The power is apportioned between the surfaces of this lens to minimize spherical aberration. A green filter localizes the wavelength of the light in the observed field to the green mercury line. For some purposes a camera with which a record of the interference pattern may be made

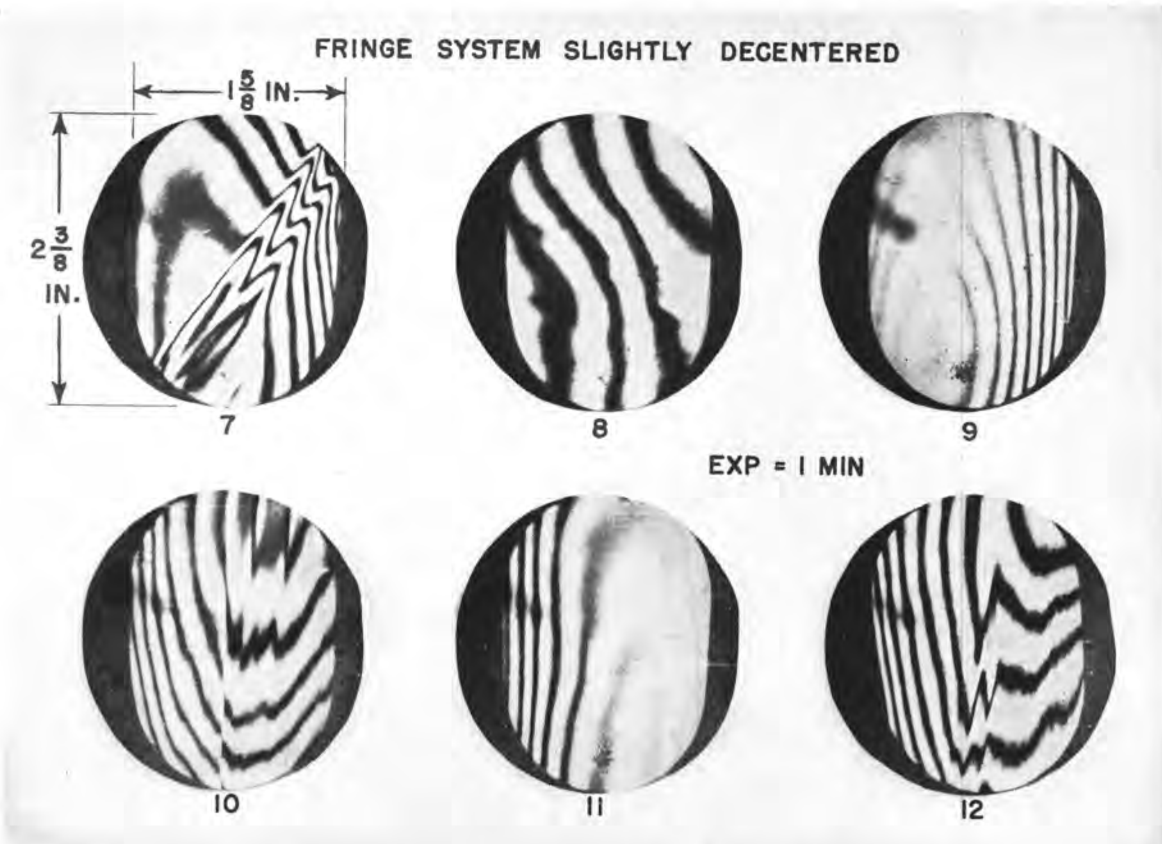

FIGURE 37. Interferometer patterns for sample M-10 periscope head prism.

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is attached to the instrument in a manner shown in the photograph.

This instrument has been so designed as to facilitate the making of the adjustments required to bring the fringes into view. The principal adjustments are the following:

1. The collimator is adjusted for parallel light by autocollimation.

2. The dividing plate is properly positioned by means of its leveling screws to such a position that the image of the pinhole reflected from the movable end mirror (*F* in Figure 36) coincides with the pinhole. The movable mirror is not provided with leveling screws, since they are not needed in the adjustment.

3. The end mirror in the testing path is adjusted by means of its azimuth and elevation screws until the images of the pinhole formed by the viewing lens and the end mirrors coincide. The observer places his eye well outside the focus of the viewing lens and in general will see two bright spots. One is moved into coincidence with the other by means of the mirror adjustment. If the optical paths are of nearly equal length, interference fringes are immediately visible when the eye is moved to the focus of the viewing lens.

4. The full aperture of the system is then obtained by a slight lateral adjustment of the viewing lens if such be necessary.

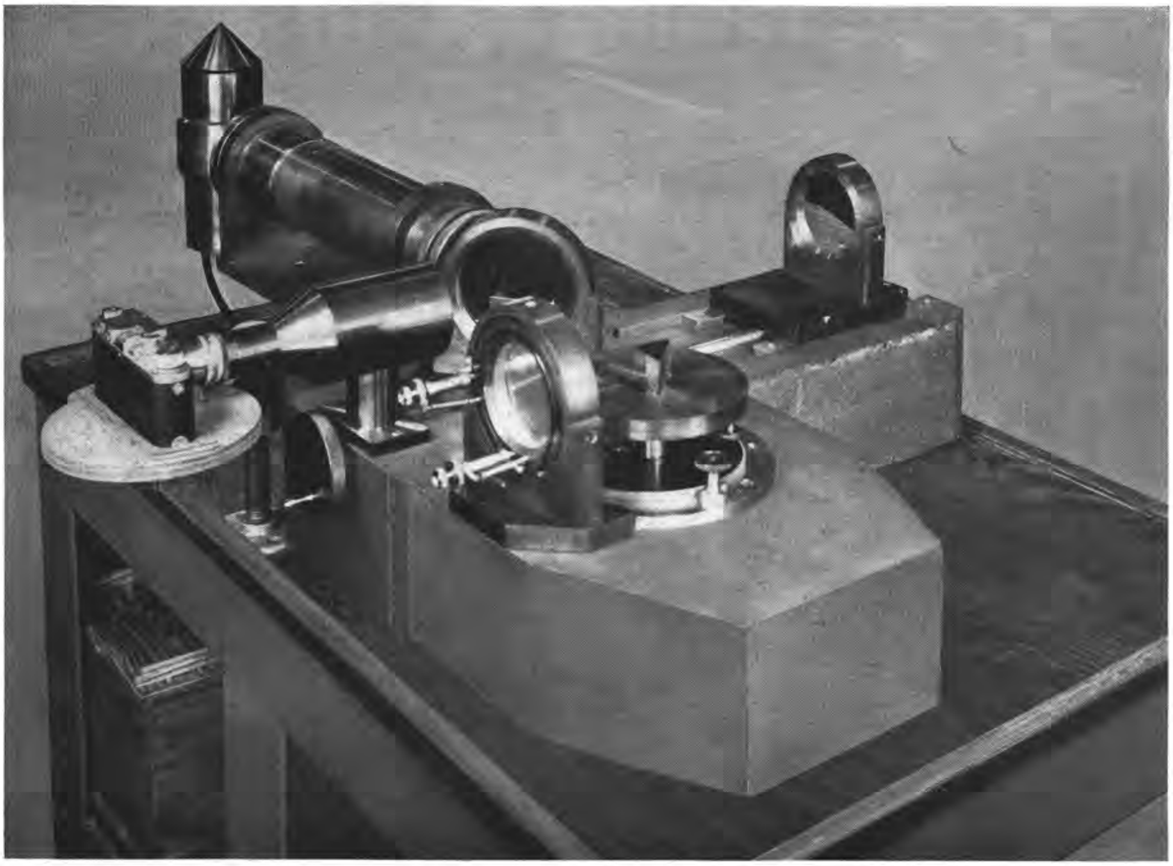

FIGURE 38. The I.1 interferometer set up for the testing of prisms.

The movable end mirror may be moved in or out until the maximum contrast of fringe system is obtained and the adjustable end mirror may be tilted by means of its screws until the desired centering or decentering of the fringes is realized.

For the testing of prisms, flats, or optical systems in which the entrance and exit beams are both collimated, the optical unit to be tested is inserted into the measuring path and

the end mirror is so placed as to return the beam through the instrument. For lenses or optical systems which normally produce convergent light, the end mirror is replaced by a reflecting spherical surface whose center of curvature is coincident with the focus of the lens or system. Arrangements for making measurements on prisms, telescopes, and lenses are shown in Figures 38, 39, and 40 respectively.

The Interferometer as a Production Test Instrument

While considerably more study of the interferometer as a production tool is desired, its use of the interferometer as a tool for the designer as an aid to the study of aberrations. And third, the interferometer may be employed in inspection for conformance with design.

In this section, only the last of these will be considered; the others are discussed elsewhere in the volume. Methods are now available for the computation of interference patterns to be expected from lenses and simple lens systems. For prisms and flats no computation is necessary since the interference fringes should be straight, parallel, and equidistant. The writer of specifications for optical parts could determine by computation or by observation on a carefully made sample the fringe system for

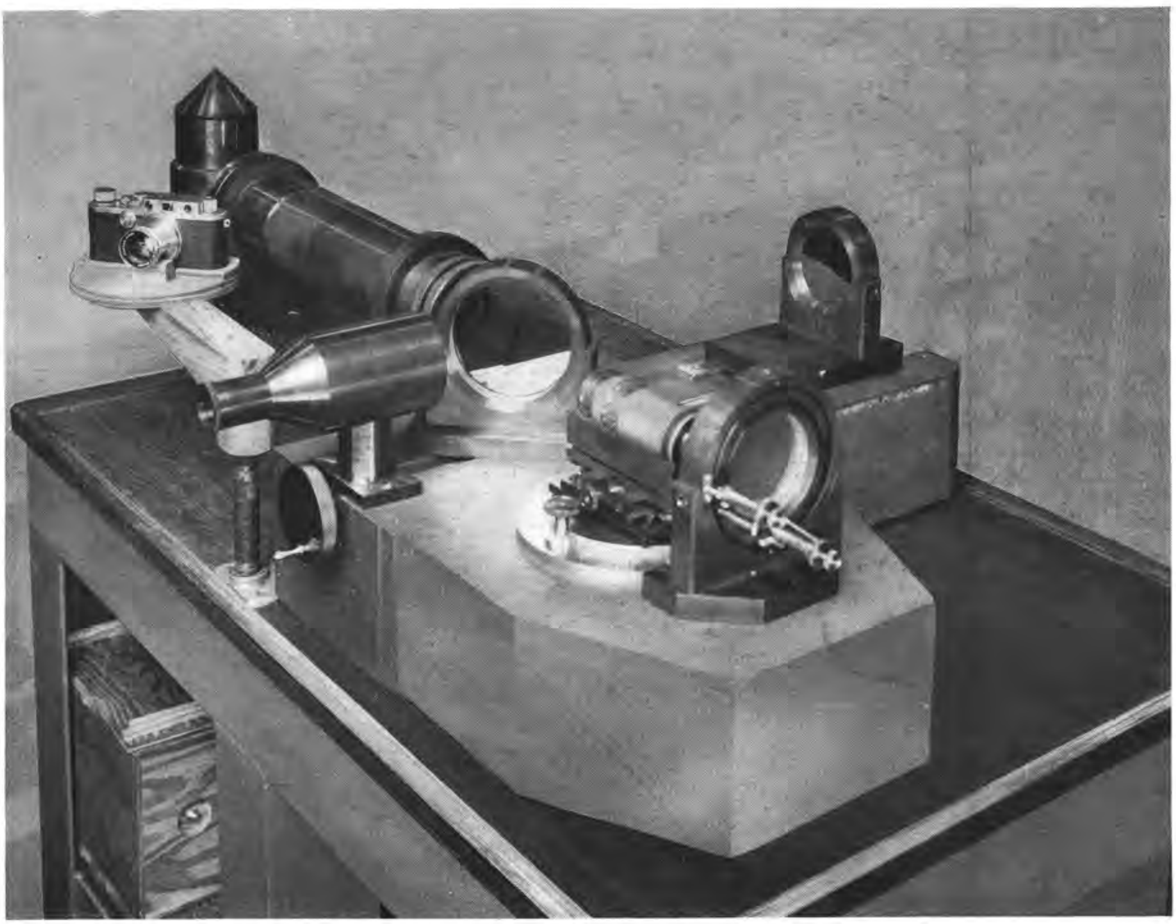

FIGURE 39. The I.1 interferometer set up for the testing of telescopes.

general usefulness is divided into three fields. First, the use of the interferometer as a guide in the figuring of individual optics. Second, the a perfect part. The effect of permissible errors in the part could be then determined in the same way and a specification indicating the re-

quired fringe system and its possible variations set up. The inspector could either count fringes or compare the field with a group of pictures of the fields produced by sample optics. If all inspectors concerned with a particular part were provided with prints of the same set of pictures, great uniformity of product could be assured.

The connection between the characteristics under examination in the interferometer and the actual performance of the instrument is not as direct as in the case of the KDC machine. The latter device is probably the more useful for the inspection of complete instruments. On the other hand, the inspection of parts and subassemblies could be carried out in the interferometer very rapidly. Moreover, the nature of the faults in rejected components may be indicated by the test.

The use of the interferometer in optical inspection is increasing rapidly. The instrument has enjoyed its greatest use in the laboratory where it has aided in the evaluation of new designs and in the production of optics which are difficult to figure, particularly aspherical surfaces. Since no large-scale testing of production instruments with interferometers has yet been carried out in this country, experience has not been accumulated on which to judge the convenience and precision of such a test.

4.3.4 The Dioptometer

During the survey reported earlier in this chapter, it was noted that an instrument called the *dioptometer* was becoming one of the most frequently used devices in the inspection of optical instruments. When this device is combined with such accessories as collimators, diaphragms, filters, and resolution charts, it may be used to inspect an optical instrument for the following:

1. Diopter setting of the reticle
2. Parallax
3. Accuracy of the diopter scale of the eyepiece
4. Astigmatism
5. Curvature of the ocular and object fields
6. Spherical aberration
7. Chromatic aberration
8. Resolution

A number of different designs of dioptometers have been developed at the Pennsylvania State College. Along with the various designs certain accessories and procedures have been evolved.

The most useful model of the dioptometer is the D-2 designed and constructed for studies at the Pennsylvania State College and at the Frankford Arsenal. Figures 41 and 42 show the instrument in use. The principal parts are

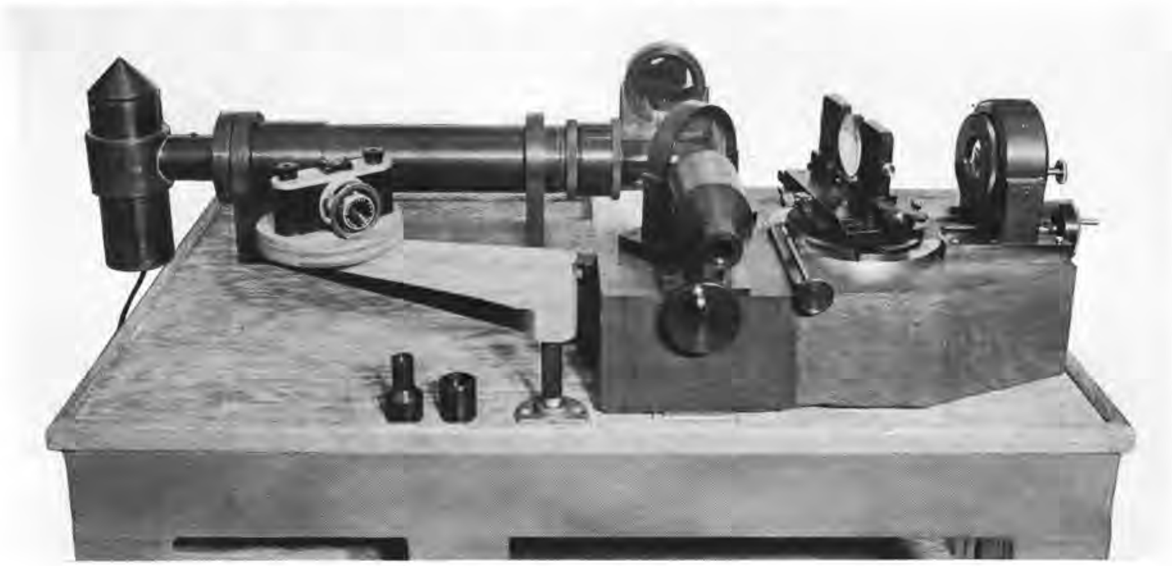

FIGURE 40. The I.1 interferometer set up for testing of lenses.

[redacted]

the objective and the eyepiece, both of which employ M-1 aiming circle optics. The eyepiece is movable and the sliding tube is calibrated in diopters from -4 to $+4$ diopters. The section of the scale from -1 to $+1$ diopter is subdivided on the drum so that measurements in this region may be made to tenths of a diopter.

The unit of the diopter is a measure of the

FIGURE 41. The Model D-2 dioptometer.

curvature of the wave fronts in a beam of light. A collimated beam has zero diopters curvature. The unit is defined as the reciprocal of the radius of curvature of the wave front expressed in meters. If the rays are converging, the sign of the unit is positive, while if they are diverging the unit is negative. Thus the light from a point source at a distance of 1 m has curvature of wave front corresponding to -1 diopter, at 2 m to -0.5 diopter and so forth. Conversely, the light from a lens converging on a point at a distance of 1 m has a curvature of wave front or power equal to $+1$ diopter, while if the focal point is at a distance of 0.5 m the power is $+2$ diopters.

THE USE OF THE DIOPTOMETER

The dioptometer measures the divergence or convergence of the light entering the eye from the eyepiece of an optical instrument. What should be the reception of such light by the eye? If the eye is directed toward an object at a great distance, the light from the object has little curvature of wave front, the power is nearly zero diopters, and an image is formed on the retina by the eye lens. As the distance to the object is decreased the curvature of the wave fronts in the light from the object increases and the power becomes more and more negative; -0.1 diopter at 10 m, -1.0 diopter at 1 m, and -2.0 diopters at 0.5 m. The eye lens changes its power for each of these cases so as to preserve the focus on the retina. A young person's eye is able to produce a good focus for objects at any distance between infinity and about 7 cm. In other words the eye can "accommodate" light with any degree of divergence between 0 and -15 diopters. The eye does not normally receive and cannot accommodate converging rays of light.

If a telescope is adjusted to produce diverging light from its eyepiece, the eye can see a sharp image provided the divergence falls within the limits just discussed. On the other hand, if the light is convergent no adjustment on the part of the eye will produce a sharp focus. The most comfortable viewing distance for most eyes when relaxed is somewhere between 1 m and infinity. For this reason most telescopes are adjusted to produce parallel light, or diverging light with a curvature not exceeding -1 diopter.

FIGURE 42. The inspection of binoculars with the D-2 dioptometer.

Cross hairs or reticles are necessary in most military instruments, and since these devices are used as reference marks against the target they should be in sharp focus when the eye is adjusted to see the target in focus. The desirable condition of complete coincidence of the

image of the target formed by the objective and the image of the reticle is rarely realized. For this reason the specification on this point generally calls for the parallax being removed at a particular mark on the reticle. This means that at this point the two images do coincide.

In order to check an instrument for this specification it is necessary to measure the relative locations of the objective and ocular fields and the reticle. Figure 43 shows several typical

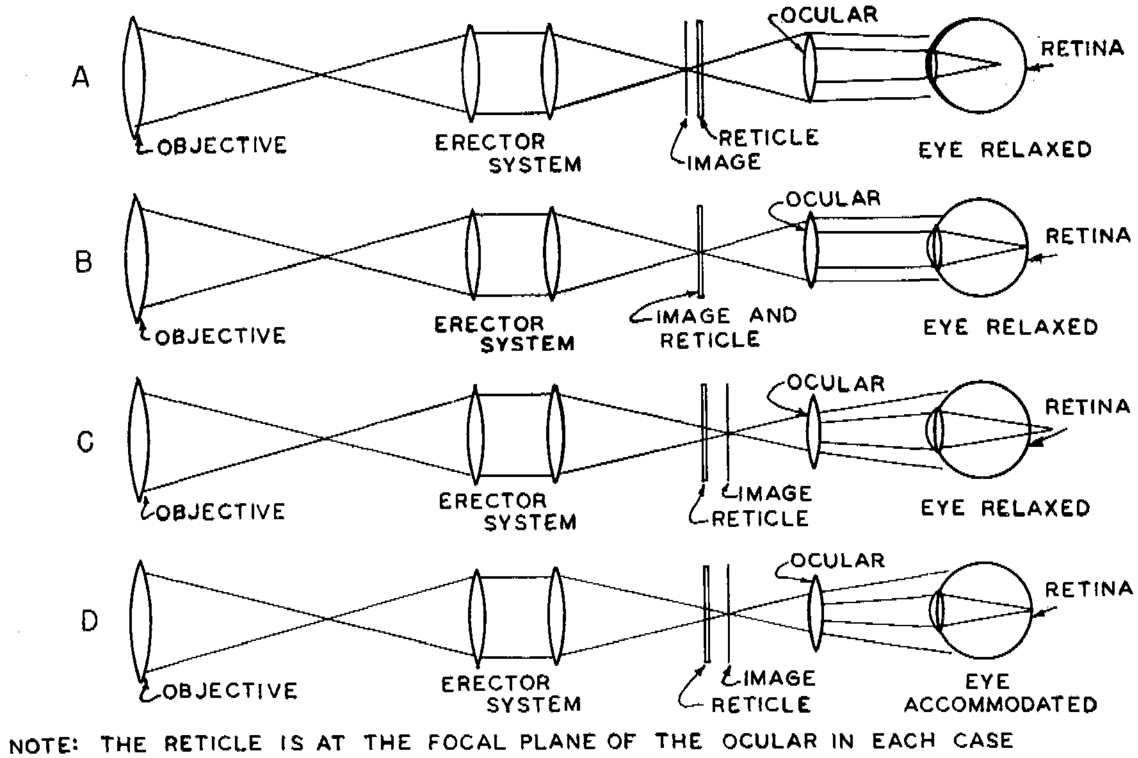

FIGURE 43. The eye as part of a telescope system.

cases. The first (A) illustrates a case in which the image of the target falls in front of the reticle and the focal plane of the ocular. The eye receives converging light from this image which it cannot focus even when the reticle is in focus. Case (B) is the ideal in that image, reticle, and eyepiece focal plane are coincident. A normally relaxed eye sees all three in sharp focus. The situations for images falling behind the reticle are illustrated in (C) and (D). In (C) the relaxed eye sees the reticle in sharp focus and the image of the target out of focus. The eye may accommodate, however, to bring the image into focus since the rays are divergent, but this throws the reticle out of focus on the retina. Under these circumstances parallax exists, for the reticle appears at a different distance than does the target.

It is in the measurement of these quantities that the dioptometer finds its greatest usefulness. As an example of the usefulness of the dioptometer, consider the measurement of setting the reticle in the desired position. In general the setting should be about 0.75 diopter negative. If an instrument is of fixed-focus eyepiece type all that is required is to focus the dioptometer on the center of the reticle field as seen through the eyepiece, and read the setting of the instrument. In the case of an instrument of variable focus, the reading of the scale on the eyepiece should be the same as that on the dioptometer.

If the instrument is mounted with a collimator adjusted to simulate a target at a distance prescribed by the specifications, the parallax may be measured for any point in the field by

first focusing the dioptometer on the image of the target at that point and then on the reticle at the same point. The difference between the two readings is the parallax. If the difference is less than 0.05 diopter, the parallax may be considered as removed.

Supplementary Apparatus for the Application of the Dioptometer

Ordinarily, the dioptometer is used in the position normally occupied by the eye behind a telescope or periscope. For convenience, a collimator is used to produce a target to be viewed by the telescope. The collimator, telescope, and dioptometer are mounted on a massive base. A set of lens caps for the measurement of spherical aberration and coma and a set of filters to aid in the determination of chromatic aberration complete the complement of accessories.

If the target of the collimator is in the form of a cross, a rapid determination of the astigmatism in a telescope may be made with the dioptometer. The telescope is rotated about its own entrance pupil and the dioptometer is rotated about the exit pupil of the telescope, through an angle equal to the original rotation times the magnification of the telescope. Figure 28 shows the relation of the parts for this measurement. At each field angle the dioptometer is focused first on the vertical bar of the cross then on the horizontal. The difference in the settings is the astigmatism in diopters. The results of a typical measurement appear in Figure 44.

If the objective of the telescope is covered by a pair of stops in turn, the first blocking all but the central zone and the second all but the margin, the spherical aberration may be quickly determined. With the first stop in place, the dioptometer is adjusted to focus on the collimated target. The adjustment is repeated with the second stop in place. The difference between the two settings is then the spherical aberration measured in diopters. In a like manner the chromatic aberration may be determined with the aid of a pair of color filters, one blue and the other red.

If the auxiliary telescope of a KDC apparatus is replaced by a dioptometer all of the above measurements may be conveniently made when the efficiency is determined.

No lengthy series of measurements have been carried through to determine the precision with

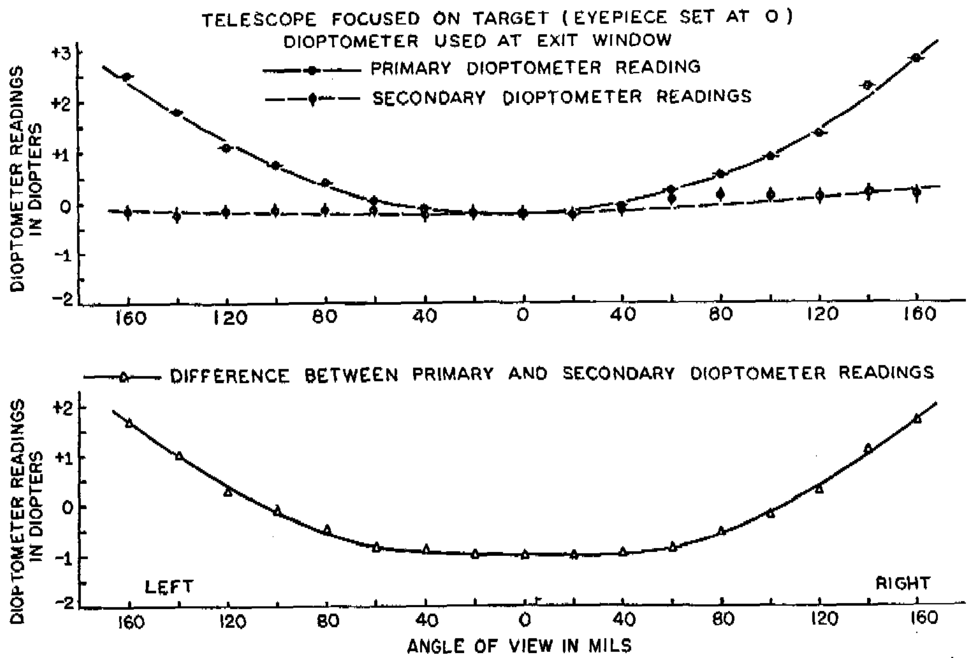

FIGURE 44. Determination of astigmatism with the dioptometer.

which the foregoing observations may be made. Thus it cannot be stated here whether these measurements are more accurate than those made by other methods. It seems clear, however, that the dioptometer is a very convenient and simple tool to use and is adequate for the control of these various factors in production testing. It should therefore enjoy increasing use as the specifications are so modified as to set forth the quantitative characteristics of production instruments.

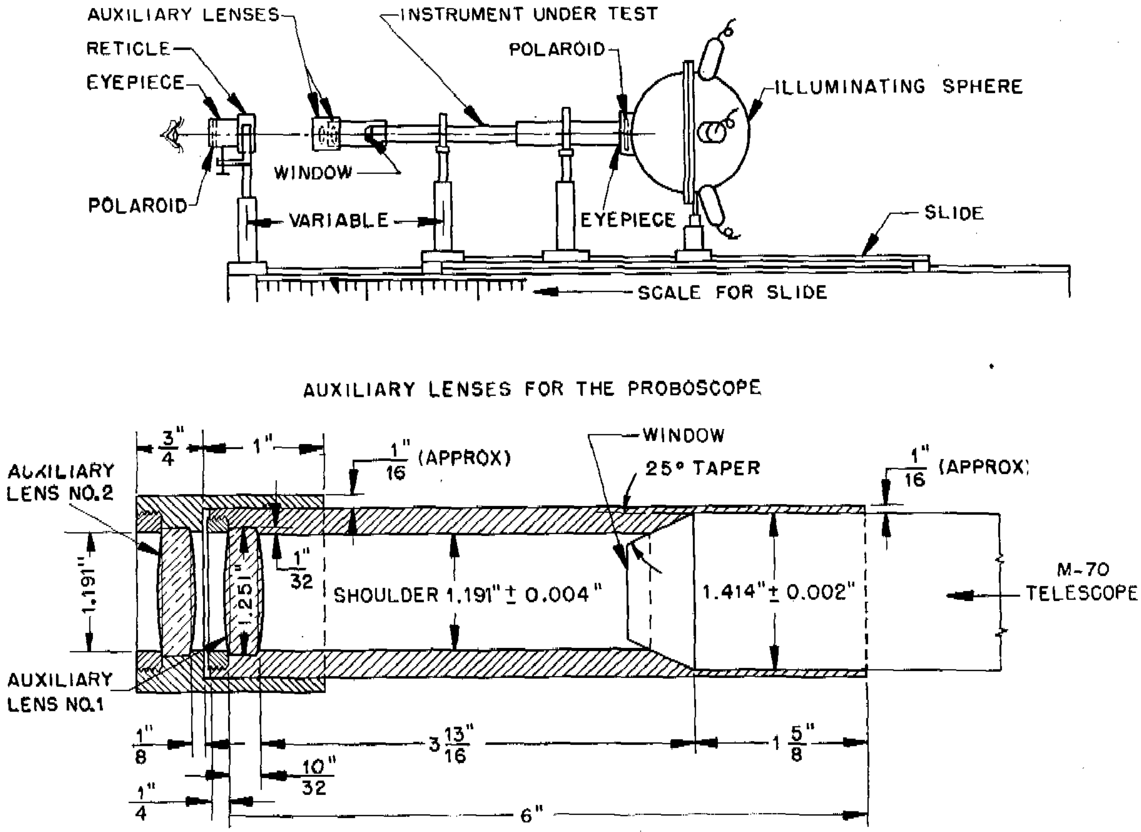

FIGURE 45. The proboscope.

4.3.5 The Proboscope

The last of the devices developed by the Pennsylvania State College group for production testing is the *proboscope*. In the section on specifications and testing (see Section 4.2), it was pointed out that each optical instrument is carefully examined for cleanliness. When dust or other marks are found on the interior optical surfaces it is often very difficult to identify the offending surface. The proboscope is designed to permit the examination of each surface in turn without disassembly of the instrument. Figures 45 and 46 show the construction of this device.

The apparatus consists of four major parts:

1. A movable slide with appropriate mounting brackets for holding the instrument under inspection.
2. An illuminating sphere.
3. Two auxiliary lenses and adapter.
4. A special eyepiece containing a reticle mounted in its focal plane.

The purpose of the movable slide is to permit the motion of the telescope and illuminating sphere and auxiliary lenses when they are required to such positions as to permit the examination of each lens surface through the eyepiece. The auxiliary lenses form real images of

the internal surfaces at the reticle of the eyepiece.

When the proboscope is first set up for each type of telescope to be tested, one telescope is disassembled and each surface is marked with a number. By trial and error, the location on the slide required to bring each number into focus is determined. Thereafter each surface in subsequent telescopes may be examined by returning the slide to the known position.

While the proboscope is not used at present

FIGURE 46. The proboscope.

to any great extent, it is felt that its use would greatly aid in the inspection of surface defects in completed instruments. Since the location of the defects may be determined, the correction of defects either by replacement of the offending lenses or by cleaning of the proper surfaces could be done with a minimum of effort.

4.4 THE EVALUATION OF DESIGNS AND DESIGN IMPROVEMENTS

The various instruments which have been described in the preceding sections were designed for the express purpose of aiding in the production testing of optical parts and instruments. The actual results obtained with these instruments, in particular with the KDC apparatus and the interferometer, for any particular optical instrument being tested, depend on the optical design of that instrument as well as the quality of manufacture. These devices may be used, therefore, to assess the quality of the design as well as to control inspection.

The principal optical errors inherent in the design of lenses or multiple lens instruments, other than chromatic errors, are spherical aberration, astigmatism, and coma. The observations and measurement of the first two of these have been mentioned in connection with the dioptometer, which has proved to be a convenient instrument for this use. The question arises as to the effects of these aberrations on the results given by the KDC apparatus and the interferometer. To study this problem, three new optical instruments were designed and built, either by or at the request of the Pennsylvania State College group. These devices are known as the *spherical aberration modifier*, the *astigmatism modifier*, and the *coma modifier*. Each instrument was designed to be as free as possible from aberrations other than the one desired. The desired aberration is introduced in such a way as to be variable and under the control of the operator.

When considering the aberration of lenses or lens systems, the concept of the Rayleigh limit is very useful. If the optical system is perfect, all rays of light starting from a point in the object pass through the entrance pupil and the optics and reach a single point in the image after traveling over exactly equal optical path lengths. Only rays which are not skew, that is, only rays which lie in planes containing the optical axis of the system, will be considered here.

In an imperfect instrument, the rays starting from a point in the object will not converge on a point in the image but any two of them will intersect at some point. The light-path length from the point in the object to the point of intersection will not be equal, however. The degree of this inequality is a measure of the magnitude of the errors.

Lord Rayleigh, thinking along these lines, postulated that if the path lengths differed by one-half a wavelength, the error would be just detectable by the eye. This path difference of one-half wavelength will be called a Rayleigh limit. It has been found in practice that one

Rayleigh limit is actually very nearly the limit of detectability.

For convenience, consider light proceeding from a source at infinity, composed of rays which are parallel when they enter the lens or lens system. The optical path for a ray reaching some point P via an arbitrary point Q in the lens or lens system is in general different from the path length to the same point P for a ray passing through the optical center, O. The optical path difference is

$$OPD = \frac{\Delta L' r^4}{4S^2 f^2} + \frac{A}{2f^2} r^2 (1 + 2\sin^2\theta) + \frac{br^3}{2S^2 f^2}\sin\theta + \frac{\Delta L}{f^2} r^2 + \frac{2\Delta h}{f} r \sin\theta + \frac{2\Delta t}{f} r\cos\theta, \quad (1)$$

where S and f are the semi aperture and the focal length of the lens; A is the astigmatism, the difference between the sagittal and tangential foci; $\Delta L'$ is the spherical aberration, the difference between the axial and marginal intercepts for parallel light; b is the coma, the distance from the paraxial image to the intersection of diametrically opposite marginal rays for an off-axis object point; r and θ are the polar coordinates of the point Q with respect to O; ΔL, Δh, and Δt are the rectangular displacements of the point P from the ideal image point.

One Rayleigh limit for spherical aberration is $4\lambda f^2/S^2$, for astigmatism $\lambda f^2/S^2$, and for coma $2\lambda f/S$. The relation between these expressions and the preceding equation is pointed out in Section 4.4.2 in connection with the interferometer. It should be mentioned that, to a good approximation, the path differences for each type of error add to produce a total error. For example, if a particular lens has 3 Rayleigh limits of spherical aberration, 3 of astigmatism, and 2 of coma for a particular point in the image, the total error will be characterized by 8 Rayleigh limits, which is very poor indeed.

4.4.1 The Yerkes Spherical Aberration Modifier

The *spherical aberration modifier* was designed at the Yerkes Observatory under Contract OEMsr-1078. The purpose in constructing this instrument was to provide a means for evaluating the effects of pure spherical aberration on the performance of fire-control instruments. Figure 47 shows the optical design of the instrument and Figure 48 shows the complete modifier. The spherical aberration is introduced by changing the position of the movable thick meniscus lens. The range is from 0 to 9 Rayleigh limits.

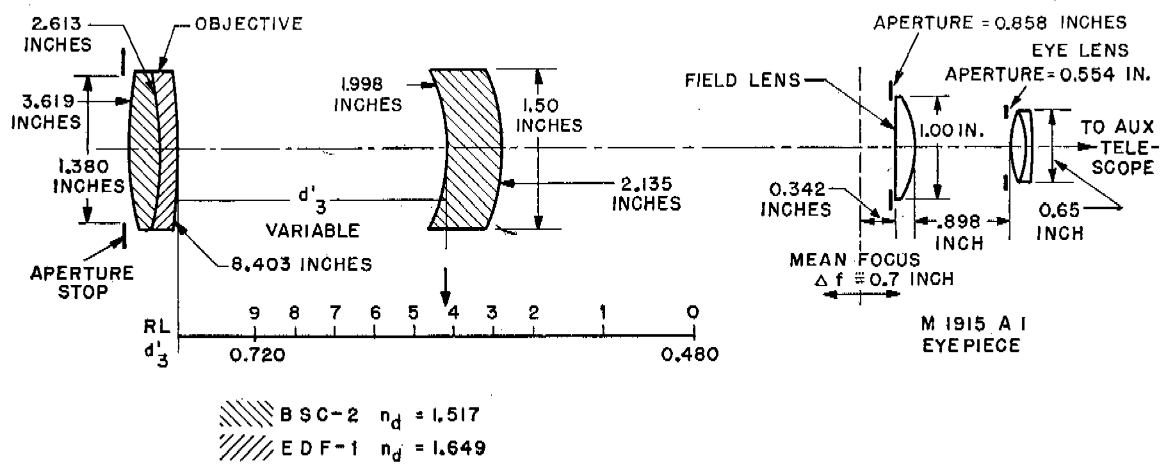

FIGURE 47. Optical design of the spherical aberration modifier.

The effect of spherical aberration as produced by the modifier on KDC efficiency is shown in Figure 49. The efficiency is 100 per cent for zero aberration, as it should be, and falls off for both positive and negative values. Over the range of the observations, the relation between efficiency and the number of Rayleigh limits is linear. Minus-eight Rayleigh limits

reduces the efficiency to about 68 per cent. There is some indication that on the plus side the efficiency drops much more rapidly.

An eyepiece containing +3.6 limits of spherical aberration may be used to extend the range in the positive direction. With this combination, measurements indicate that the KDC efficiency drops to 70 per cent at about +3.8 limits.

FIGURE 48. The spherical aberration modifier.

The fringe system produced by the modifier when it is placed in one of the light paths of the interferometer may be computed by means of equation (1). Remember that the interferometer measures path length differences directly. For spherical aberration

$$OPD = \Delta L' r^4 / 4S^2 f^2.$$

The number of dark fringes n observed in the pattern is $n\lambda = \Delta L' S^4/4S^2f^2$. Thus $\Delta L' = 4n\lambda f^2/S^2$. The value of $\Delta L'$ for one Rayleigh

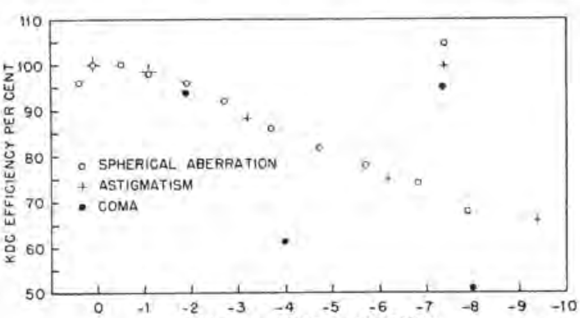

FIGURE 49. KDC efficiency as function of spherical aberration.

limit of spherical aberration is $4\lambda f^2/S^2$. The amount of spherical aberration possessed by the lens is the number of rings in the interferometer pattern times the value of spherical aberration for 1 Rayleigh limit. There is one fringe for each Rayleigh limit of aberration, as is to be expected from the definition of the Rayleigh limit. Figure 50 shows clearly the agreement between the predicted fringes and those observed with the modifier. A count of the observed fringes shows that the correct number appears in each case. The application of the interferometer to the measurement of the spherical aberration in a production telescope is shown in Figure 51.

4.4.2 The Astigmatism Modifier

With the success of the spherical aberration modifier, described in the preceding section, it seemed likely that a similar device designed to introduce astigmatism into an otherwise perfect optical system would be of considerable use. The device developed consists of an objective and an eyepiece, both of which are M-1 aiming circle optics mounted together in a tube to form a small telescope of magnification 4×. The variable astigmatism is introduced by rotating the objective about an axis through its second nodal point. The objective is so corrected as to be free from spherical aberration on the axis. The coma remains nearly constant and small, since it is zero on the axis, so that over a wide range of angles of rotation the device produces images of object points on the axis in which astigmatism may be varied without any significant amount of coma.

Figure 52 is a diagram of the optics of the *astigmatism modifier*. The figure shows an auxiliary telescope which is properly part of the KDC apparatus and does not contribute to the function of the modifier. The amount of astigmatism introduced at each rotation angle of the objective may be determined in several ways. The computations, while not as simple as in the case of spherical aberration, are straightforward. The technique described in the discussion of the dioptometer for the direct measurement of astigmatism is applicable here as well. The curve relating the astigmatism to the rotation is smooth and approximately parabolic in shape. At zero angle the astigmatism is zero while at 10 degrees the astigmatism is about 160 Rayleigh limits. For the optics em-

ployed in the modifier, this corresponds to about 0.090 in difference in focal length for sagittal and tangential foci. The construction of the modifier is illustrated in Figure 53. Because of the fact that small angles of rotation produce large amounts of astigmatism, the motion of the objective is controlled by a screw and lever arrangement.

astigmatism is placed in an interferometer and the fringe system is centered, the optical path differences will be given by the terms in the equation with r^2 coefficients. Thus

$$OPD = Ar^2 \frac{(1 + 2\sin^2\theta)}{2f^2} + \frac{\Delta L r^2}{f^2}.$$

The interferometer pattern will have a maximum number N of fringes across one diameter

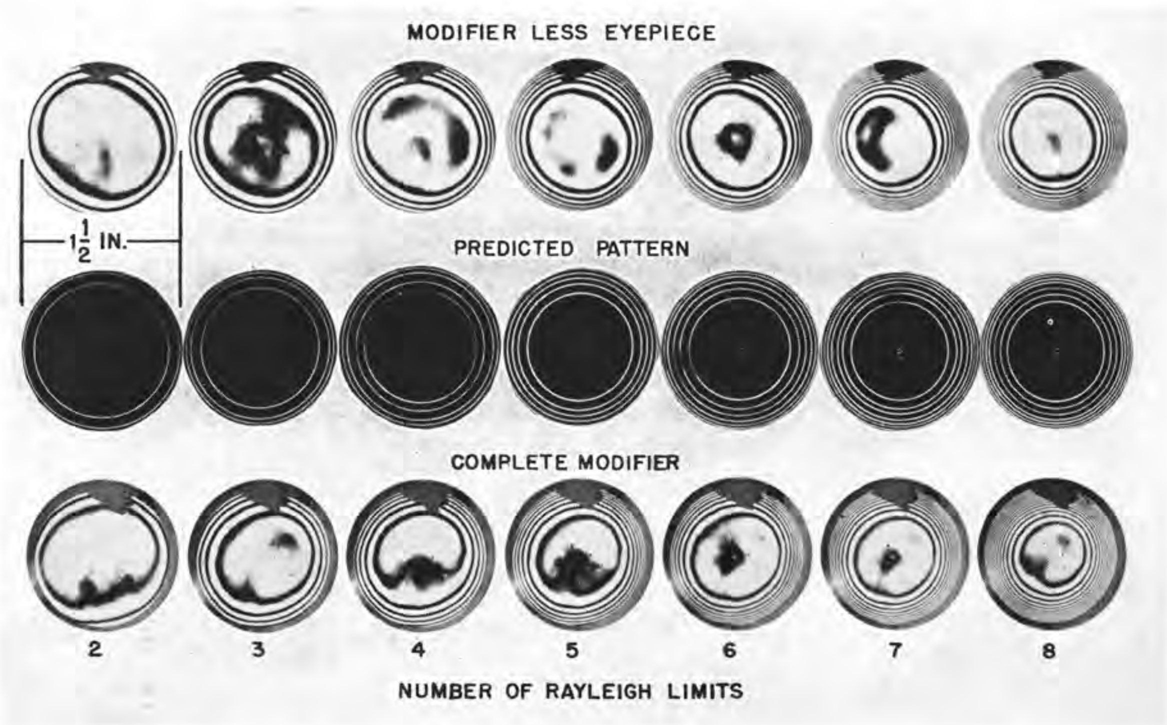

FIGURE 50. Interferometer patterns for the Yerkes spherical aberration modifier.

The effect of astigmatism in the objective of an optical instrument upon the KDC efficiency of that instrument may be readily observed by measuring the efficiency of the modifier for various settings of the rotation angle. The crosses of Figure 51 show the relation between the efficiency and the number of Rayleigh limits of astigmatism. The shape of the curve is very nearly the same as it was for the spherical aberration.

Equation (1) which permits the computation of the optical path differences may be used to predict the interferometer pattern for astigmatic images in the same way as it was used in the preceding section for spherical aberration. If a lens or telescope possessing only

and a minimum number n across a diameter perpendicular to the first. Then

$$N\lambda = \frac{\frac{3}{2}AS^2 + \Delta LS^2}{f^2},$$

and

$$n\lambda = \frac{\frac{1}{2}AS^2 + \Delta LS^2}{f^2}.$$

Upon subtraction

$$(N - n)\lambda = \frac{AS^2}{f^2}.$$

The term $N - n$ is the difference in the number of fringes across the two diameters.

The amount of astigmatism A is

$$A = \frac{(N - n)\lambda f^2}{S^2}.$$

The factor $\lambda f^2/S^2$ is 1 Rayleigh limit of astig-

matism. Thus, for a lens possessing essentially astigmatism, the differential number of fringes in the interferometer pattern is independent of the focus when the fringe system is centered and the value of the astigmatism is the differential number of fringes times the value of one Rayleigh limit for astigmatism. Conversely, the number of Rayleigh limits is, under the same conditions, equal to one-half the differential number of fringes. A comparison of the theoretical and the observed patterns for about 2.2 Rayleigh limits appears in Figure 54. The agreement is very good. When the fringes appear hyperbolic, at the best focus those across one diameter must be counted as negative and thus the difference becomes the sum of those visible. In each view the difference is a little less than six.

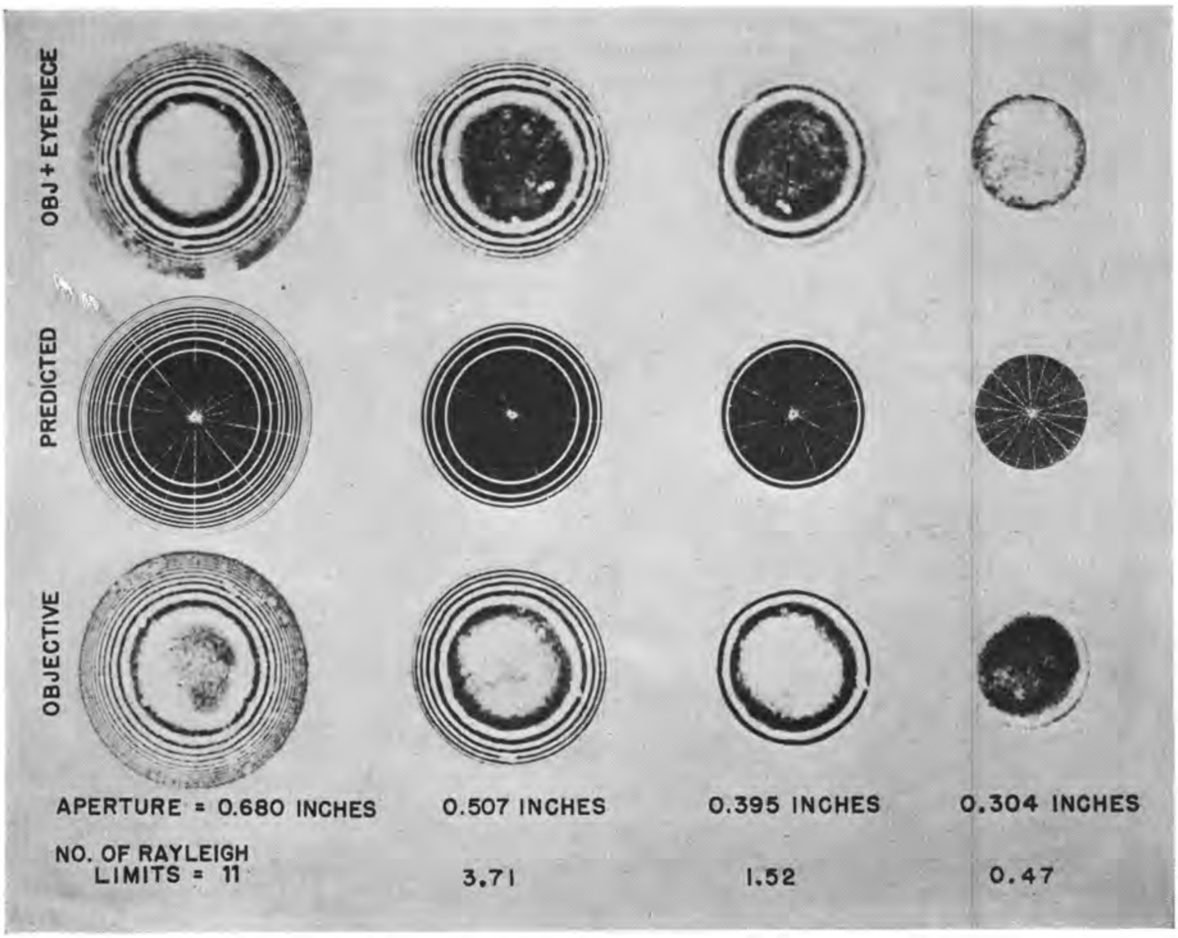

FIGURE 51. Interferometer patterns for an M-1 aiming circle.

4.4.3 The Coma Modifier

To complete the study of the effects of the first-order aberrations, a device for the introduction of coma into an optical system was desired. A special objective containing spherical aberration was designed at the Yerkes Observatory. The Perkin-Elmer Corporation manufactured this lens and a standard M-1 eyepiece completed the telescope. As before, this device, known as the *coma modifier,* produces images containing nearly pure coma. The objective is pivoted about a point some distance back from the lens itself. The lens has a diameter of approximately 2 in. A stop at the pivot point limits the effective aperture to 1.41 in. The optical design is shown in Figure 55. Because of the restrictions on the design, the

[redacted]

modifier has 0.8 Rayleigh limits of spherical aberration and some astigmatism. The spherical aberration is constant and may be subtracted from the coma. The astigmatism, however, is zero on the axis, that is, for a zero angle of rotation, and increases to 2 Rayleigh limits at 2 degrees rotation. At this angle the coma is 10 Rayleigh limits. The relation between the number of Rayleigh limits of coma and the angle of rotation is linear, according to computation, from zero at zero angle to 10 Rayleigh limits at 2 degrees. A photograph of the modifier appears in Figure 56.

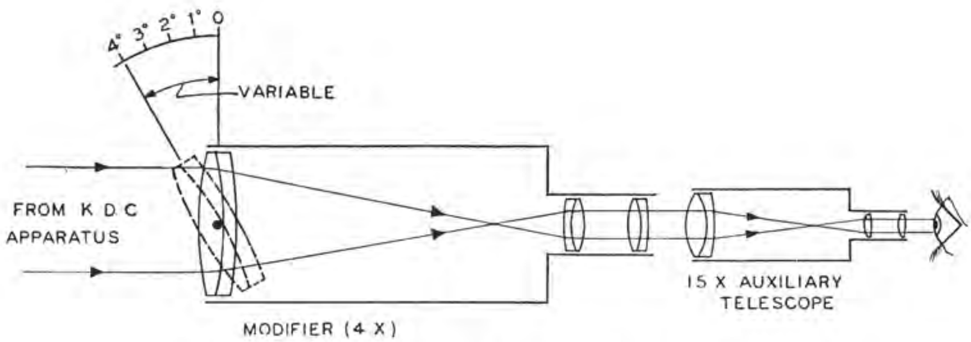

FIGURE 52. Optical design of the astigmatism modifier.

FIGURE 53. The astigmatism modifier.

The efficiency measurements for the coma modifier in the KDC machine appear as closed circles in Figure 51. It may be seen clearly that for more than 4 Rayleigh limits, coma has a greater effect upon the KDC efficiency than does either the spherical aberration or the astigmatism. This point is of considerable importance to the designer for he should reduce this coma even at the expense of the other aberrations if he wishes to improve the resolving power.

If the modifier is placed in an interferometer, adjustments are made to center the fringe system, and the end mirror is set for paraxial focus, then by equation (1)

$$OPD = \frac{br^3 \sin \theta}{2S^2 f}.$$

Along one diameter, then, the number of fringes will be a maximum where $\sin \theta = 1$.

Then

$$N\lambda = \frac{bS^3}{2S^2 f},$$

and

$$b = \frac{2N\lambda f}{S}.$$

Now 1 Rayleigh limit for coma is $2\lambda f/S$ so, as in the case of the other aberrations, there is one fringe for each Rayleigh limit of coma. In other words, the value of the coma is the number of fringes times the value of 1 Rayleigh limit for coma. Figure 57 shows the observed

[redacted]

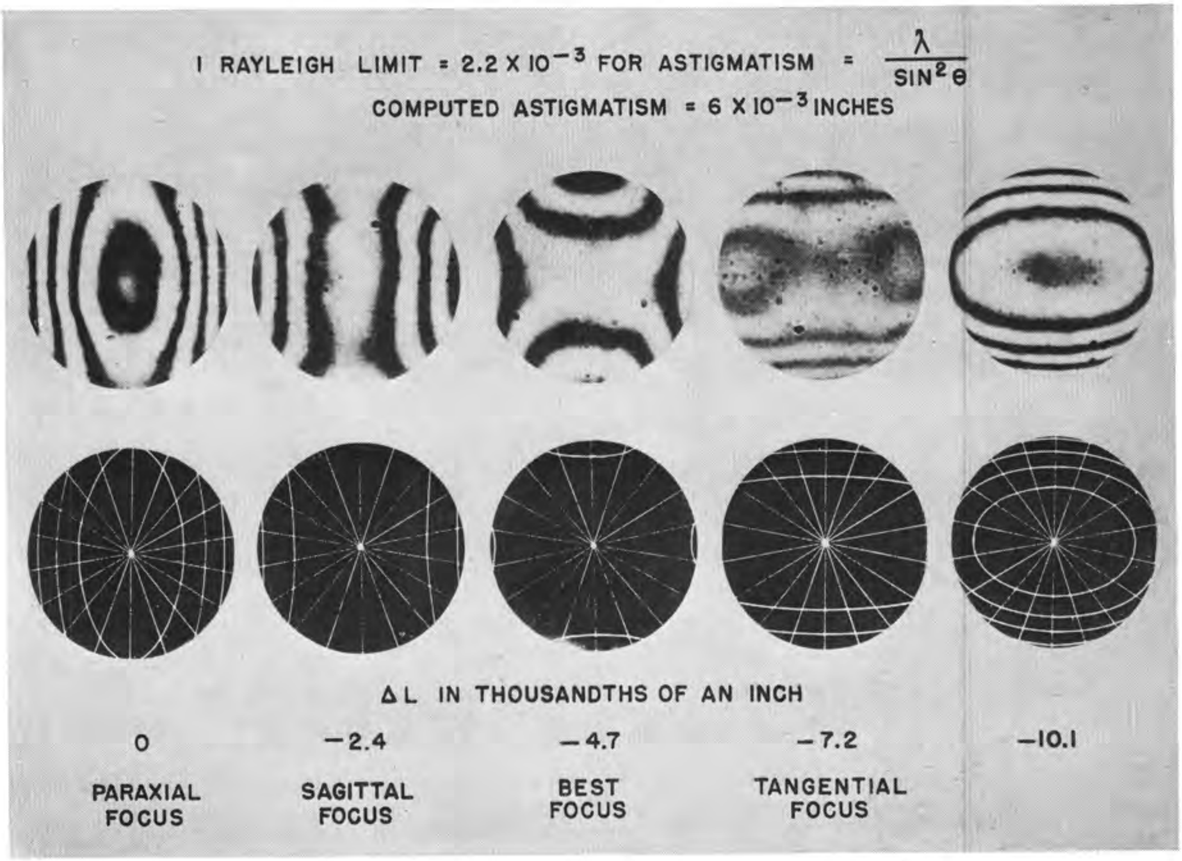

FIGURE 54. Interferometer patterns for the astigmatism modifier.

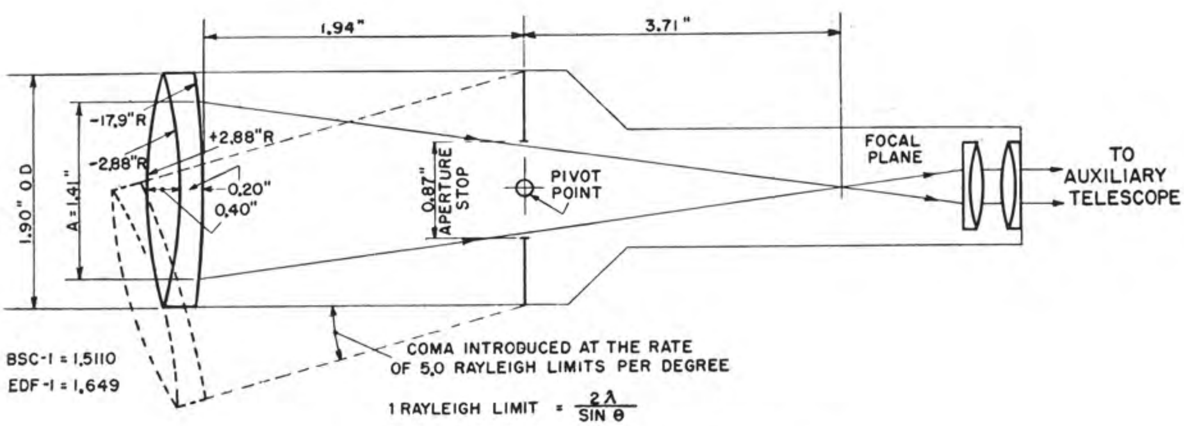

FIGURE 55. Optical design of the coma modifier.

[redacted]

and computed interferometer patterns for several values of the angle of rotation of the objective in the coma modifier and thus for various values of coma. As before, the agreement is very good.

4.4.4 Survey of Results from Aberration Modifiers

The various aberration modifiers have fulfilled two purposes. First, they have permitted the exact determination of the effect of various amounts of each aberration upon the KDC efficiency and thus upon the resolving power of an instrument. Second, they have provided a means of checking the computations of interferometer fringe patterns. These functions are, of course, directed toward the designer of new or improved optical systems, but they will also aid in the analysis of present systems with a view toward their improvement. A telescope now in production may have a low KDC efficiency even under the best conditions of workmanship. It may be that interferometer patterns show that one or more of the aberrations is greater than it should be for the desired performance of the instrument. Then, by trial and observation with the interferometer, changes in the optics may be made to improve the performance. Thus an observational approach may partially replace laborious computational methods.

FIGURE 56. The coma modifier.

4.4.5 The Artificial Sky Apparatus

The *artificial sky apparatus* [ASA] consists of an internally illuminated sphere and a camera. The function of the sphere is to simulate conditions of a bright natural background. The instrument being tested looks through the sphere and out at a target, through an aperture on the far side of the sphere. Figure 58 shows the arrangement of the parts. The sphere does not cut into the true field of the instrument, so that any light from the sphere that reaches the camera must be scattered at least once inside the telescope. The actual illumination of the surface of the sphere depends upon the number of 7.5-w bulbs used. For one bulb the level is 37 foot-candles, while for all six a level of 217 foot-candles is available.

Because of differences in various types of telescopes, two spheres were built, one for use with M-71 telescopes and one for M-72 and M-76.

Two targets of the bull's-eye type are convenient for use with the scattered light experiments. One has a white center, illuminated at 10 foot-candles, and a black surrounding zone, while the other has a black center and white outer zone.

Nearly all the measurements were made by photographing the target through the telescope, first with the lights of the ASA off and again with them on. Transmission measurements of the negatives made with a Leeds and Northrup microphotometer and recorder gave graphical records of the results, but the negatives were not photometrically calibrated, and so the results are only qualitative. Care must be exercised to insure that the quality of the light in the sphere and on the target are the same, otherwise the color sensitivity of the film becomes important.

The principal results of a study of six telescopes, two M-71, two M-72, and two M-76, are:

1. A considerable amount of scattered light enters all of the telescopes. This cannot help

but reduce their usefulness under bright conditions.

2. A considerable loss of contrast in the target results from the scattered light.

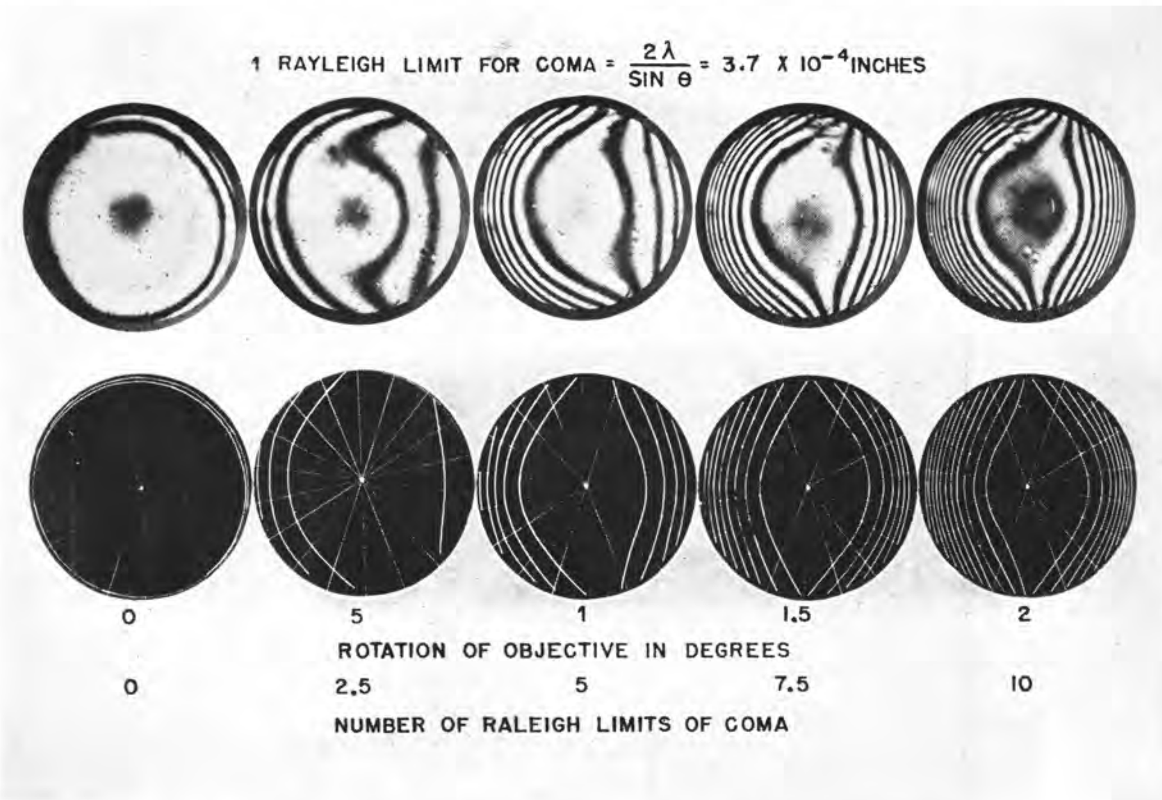

FIGURE 57. Interferometer patterns obtained with the coma modifier.

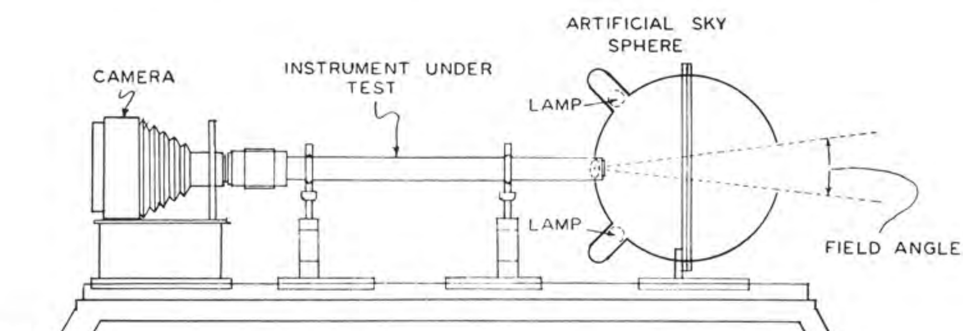

FIGURE 58. The artificial sky apparatus.

3. The actual amount of scattered light varies from instrument to instrument, even of the same design.

A result of considerable interest concerns the effect of coated optics. The coating of optics of telescopes is employed to reduce the loss by surface reflection and thus increase the transmission of the instrument. What effect does such a coating have on the scattered light? Two good M-71 telescopes, one with coated optics and one without, were observed visually, each by two observers. Both had about the same

[redacted]

KDC efficiency when measured in the normal way. When used with the ASA, slightly more light seemed to be scattered by the instrument with coated optics. The bull's-eye targets without the ASA, however, gave preference to the coated telescope. From these simple experiments it appears that coating optics makes little difference in the scattered light and if there is any difference it is in the direction of more scattering when coated. On the other hand, the increased transmission made the coated telescope much more useful for targets of low contrast at low levels of illumination.

The ASA has been used in another way, namely, in measuring the effect of striae. A block of glass to be observed for striae is placed in the telescope between the objective and its focal plane. The increase in scattered light from the ASA, and thus the change in the KDC efficiency of the telescope, becomes a measure of the effect of the striae. A second method has been to examine the contrast of the bull's-eye target with and without the block of glass placed before the objective. When in place the block is illuminated from the side.

It is regrettable that the termination of the work before a large group of sample blocks of glass became available prevented thorough testing of this method for the determination of the effect of striae.

4.4.6 Photoelectric and Photographic Procedures for the Evaluation of Optical Instrument Design

As an aid to the lens designer, one of the most useful kinds of information would be the results of experimental ray tracing. The Hartmann test, which involves covering the aperture of the objective with a diaphragm containing a number of small holes and observing the direction of the rays passing through the various holes, gives this sort of information. The test requires a large amount of careful measurement, however, and is time consuming. A less difficult, and perhaps more practical, determination is that of observing the distribution of intensity in the region of the image since this depends on the integrated contribution of rays over the entire aperture. Since most requirements relating to telescope performance involve the resolution of parallel lines or the discrimination of the edges of objects, it seems most useful to study the energy distribution in the image of a line source.

Equipment has been developed for recording the energy distribution in the image of a distant line source produced by a telescopic system and focused on a plane at a considerable distance behind the eyepiece. Both photoelectric and photographic methods were employed. Figure 59 is a diagram of the photoelectric scanning apparatus. The device is a modified KDC machine. The original target has been replaced by a line source which may be mounted either in a vertical or horizontal position. The auxiliary telescope is not used but in its stead a scanning slit and phototube assembly are employed. This assembly travels slowly across the image in a direction perpendicular to the optical axis. The electrical output of the photocell is recorded on a recording microammeter, which shows directly a plot of light intensity across the image.

Figure 60 illustrates the instrument modified for photographic recording. The image of the line is photographed through a wedge whose gradient of density is parallel to the line source. Figures 61 and 62 are typical results obtained by the two methods under the same conditions and with the same telescope.

Two results are obtainable from the type of observations illustrated in the figures. The records, either photoelectric or photographic, indicate the manner in which the image quality deteriorates with a change of field angle. Results of this type permit an analysis of the region of confusion, including the effect of skew rays, in a far shorter time than would be required by ray tracing and thus serve as an effective basis for evaluation of lens design.

4.5 CONCLUSION

The optics group at Pennsylvania State College has made a complete survey of the methods of inspection of optical instruments. While this was their primary task, together with

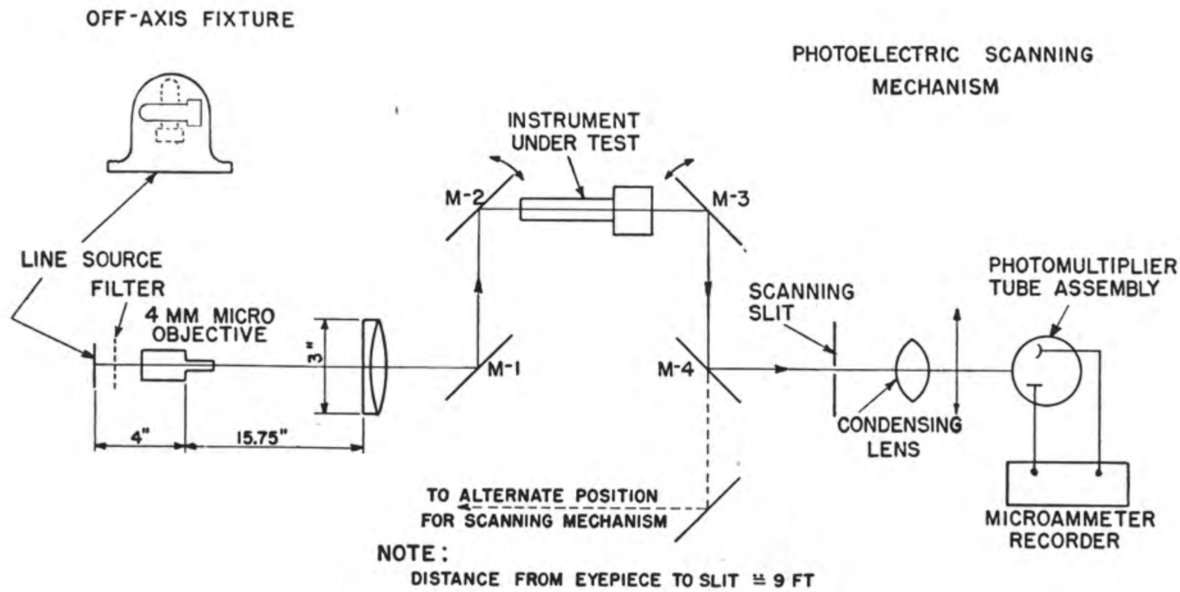

FIGURE 59. The photoelectric KDC machine.

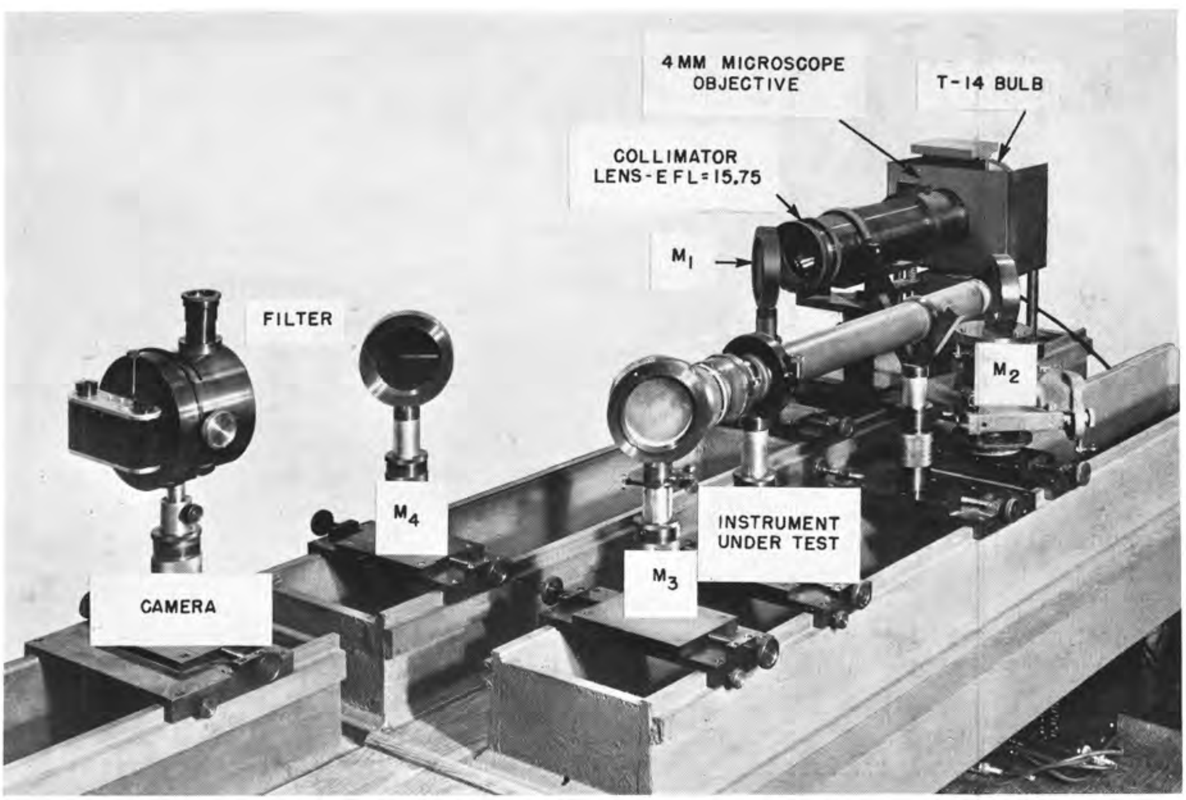

FIGURE 60. The photoelectric KDC machine. A camera replaces the photocell.

[redacted]

recommendations for changes in methods where such were indicated, they have in addition developed numerous instruments and devices to aid in the testing procedures. Among these the *kinetic definition chart apparatus* has come to play a major role in the testing of the definition of certain classes of tank telescopes. The *interferometer*, while not so widely used as yet, has been demonstrated to be of considerable use in the determination of the quantitative behavior of optical components and complete instruments. These two devices represent a group which were designed to aid in the placing of the entire method of specification on a more quantitative basis.

During the survey of methods of inspection it was found that many of them depended upon the subjective observations of the inspector. It is recommended that as many such cases as possible should be replaced by quantitative measurements. When such measurements are introduced it has been found that many instruments which pass the inspection are by no means as well constructed and thus behave as well as others of the same design. There is good indication then that, for such cases, studies of manufacturing methods could lead to general improvement in the performance without design change.

Perhaps the most significant result of the survey is the recommendation that the specifications be reexamined to determine whether they, in reality, control the production in such a way as to produce the greatest number of usable instruments. The necessary performance should be determined by a study of the conditions of expected use. When this has been established, the specifications should then be written so as to produce optics of the necessary quality. Factors which do not affect this quality should not be specified, and certainly no quality should carry a specification which requires the degree of perfection to be greater than demanded by the minimum acceptable performance.

The optical perfection of an overall optical system which has been established as barely acceptable should be expressed in units based

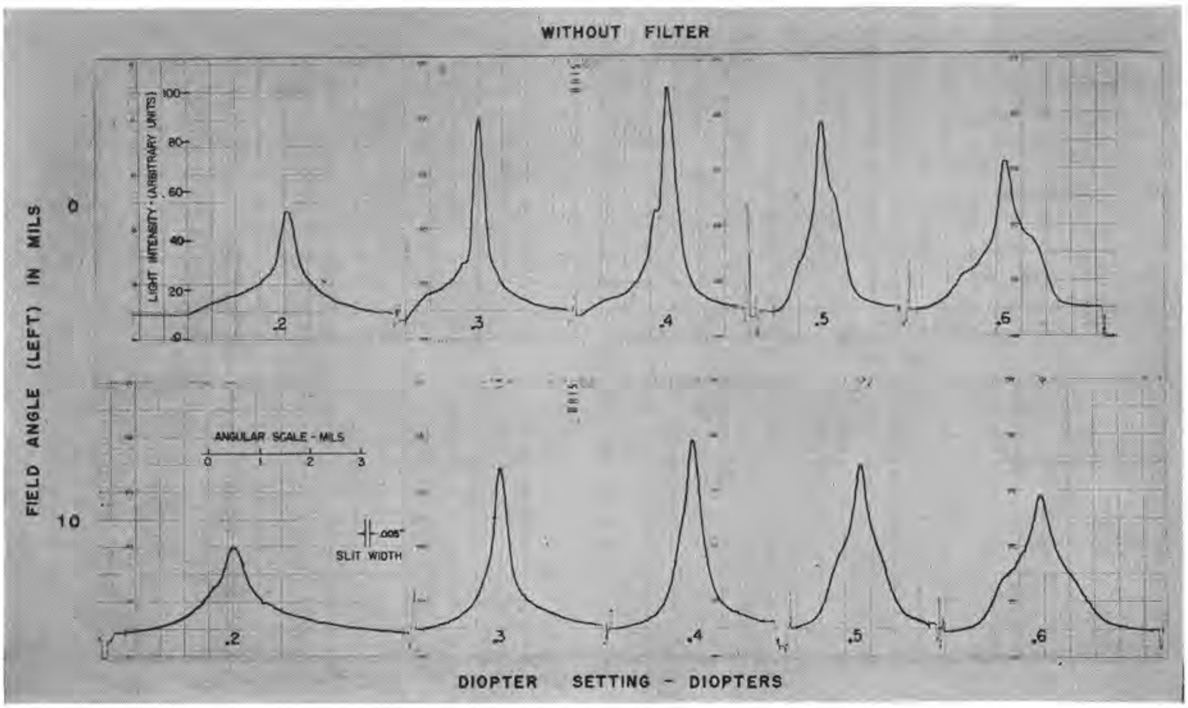

FIGURE 61. The photoelectric KDC machine records.

on the Rayleigh limit. The inspection may then be carried out on the interferometer by the simple interpretation of fringes. The variation in focal length, concentricity and alignment, spacing and mounting, and the resolution for each element which corresponds to one Rayleigh limit in overall performance of the system, should be computed or measured experimentally.

It is unfortunate that the work under this contract terminated before the Specification and Inspection Manual could be prepared. There is a need for a manual of this type and it is recommended that this work be vigorously pursued.

The KDC apparatus has been shown to be a valuable tool in optical research and design. It has been used to study fundamental concepts such as the effects of aberrations on performance, the efficiency at various angles of view, the effects of target contrast, and of component defects. However, a great deal of work yet remains to be done in adapting the use of the KDC apparatus to the study of components and the effect of their errors on the performance of the instruments as a whole.

The Michelson-Twyman interferometer has been developed to the point where it may be readily employed for inspection purposes provided the specifications are so modified as to be applicable to such measurements. Future work on the application of this instrument should assess its relative usefulness when compared to other quantitative methods. In the study of the application of the interferometer to the development of new designs, the possibility of using the instrument as a means for the investigation of the use and performance of nonspherical surfaces is attractive. There is always the possibility that the approach to new design problems can be made on an experimental basis. Such an attack would make extensive use of the interferometer.

The continued development of such instru-

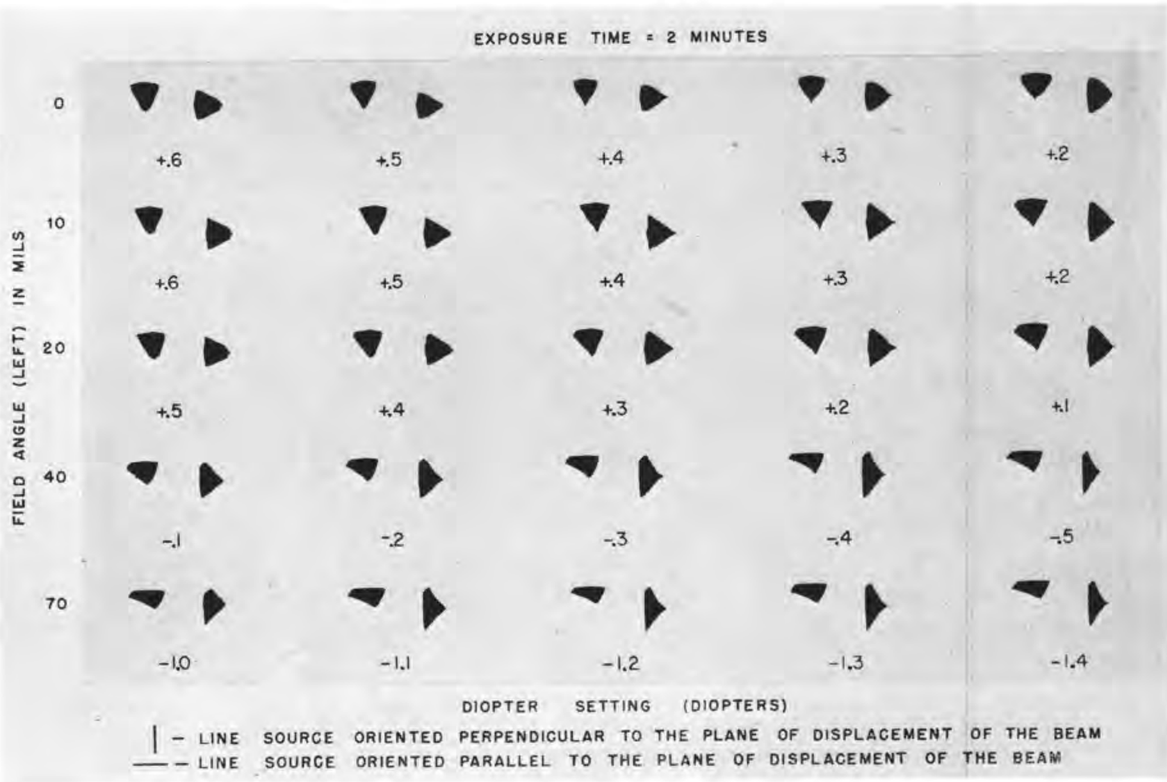

FIGURE 62. Wedge photographs of line source.

[redacted]

ments as the *modifiers* would be of great aid in establishing the minimum quality of optical instruments acceptable for military purposes. The philosophy represented in these instruments, that of measuring the results on the performance of known amounts of individual errors, could well be extended to such factors as striae, scattered light, misalignment, surface defects, and so on.

The general tendency toward automatic recorders such as photoelectric KDC machines should be continued as new electronic techniques become available. All ways in which the judgments of the observer may be removed or made less important should be exploited. The photoelectric scanning of images is a development of this type. It may be safely predicted that at some time not too far in the future a completely automatic inspection of optical instruments will be possible.

4.6 RECOMMENDATIONS BY NDRC

1. Present specifications should be carefully reviewed for all optical instruments, on the basis of the survey that was made under NDRC and on the basis of all other available information. Specifications should be based on a level of quality adequate to insure that instruments give the performance inherent in their designs, but should not be more rigid than is necessary to achieve this result. They should be based, as far as possible, on the use of impersonal methods of inspection.

2. Present methods of inspection should be reviewed in detail. Every effort should be made to introduce objective methods so that there can be no differences of opinion as to whether an instrument meets specifications.

3. Further development work should be conducted vigorously on new methods of inspection, employing all available techniques. These should include photoelectric and automatic methods whenever possible.

4. The use of the interferometer for inspecting individual elements and subassemblies should be studied further. With adequate fixtures for making adjustments expeditiously, it seems likely that the interferometer offers one of the most promising impersonal means for carrying out inspection. Much remains to be done in the way of setting up satisfactory methods for interpreting fringe patterns and of establishing appropriate criteria for inspection.

5. Studies based on correlations with field tests of performance should be made to establish the level of efficiency that should be required in KDC tests for inspection.

6. Further studies should be made to determine the best value of auxiliary magnification that should be used with the KDC apparatus.

7. The resolving power of the naked eye, with various apertures, should be fully investigated. This program should be undertaken in close cooperation with the Army-Navy-NRC-Vision Committee, to insure that all physiological considerations are taken into account in planning the program.

8. The effect of coated optics on scattered light in telescope systems should be measured to determine whether present methods of coating lead to any loss of contrast.

9. A manual covering recommended methods of inspection should be prepared as soon as the studies outlined above have been completed.

[redacted]

Chapter 5

BINOCULARS AS AIDS TO VISION

By *H. K. Hartline*[a]

5.1 SUMMARY

Investigations of the optimum design features of binoculars for use at night was undertaken at Dartmouth College (Contract OEMsr-1058), Brown University (Contract OEMsr-1229), and the University of Pennsylvania (Contract OEMsr-1228). Tests in indoor observing ranges were made with binoculars of various magnifications and exit pupils. An evaluation was made of the physical and physiological factors governing the assistance to vision furnished by binoculars.

The range at which small targets could be detected at levels of illumination corresponding to night conditions was increased by increasing the magnification of hand-held binoculars up to 10×, using instruments with objective diameters of 50 mm and 70 mm. Further increase to 14× yielded poorer performance. Range of target detection was increased significantly by increasing the exit pupil diameter of 5× instruments up to 6 mm. Further increase yielded only slight additional gains.

Binoculars mounted in alidades yielded slightly better ranges of detection than hand-held binoculars by about 8 per cent.

The maximum gain in range of detection obtained with binoculars was 4 to 4½ times that obtained with naked-eye observation, under comparable conditions. This gain was furnished by 10× binoculars (50-mm and 70-mm objectives) at brightness levels comparable to a clear moonless sky.

The range of detection of targets is decreased by light losses within the binocular and by brightness losses resulting from failure of the instrument's exit pupils to utilize the full aperture of the pupils of the observer's eyes. Serious brightness losses result from misalignment of the instrument with respect to the eyes, caused by improper holding and aggravated by eye movements as the observer scans the field of view. In addition, angular tremor movements caused by unsteady holding and magnified by the instrument decrease the visibility of targets. Quantitative allowance for the effects of these factors on the visibility of targets with the aid of binoculars can be made with moderate success.

5.2 INTRODUCTION

The study of binoculars as optical aids to vision was undertaken by NDRC in May 1943 to provide basic information which would assist the Bureau of Ordnance in selecting the most effective optical characteristics for night binoculars. The aim of Project NO-210, which was formally established in January 1944, is described as follows: "The primary purpose of the project is to determine the optimum relation between magnification, angular field of view, exit pupil, size and weight and such other factors as may appear. The project is directed primarily at night glasses, though not necessarily so limited." Since these factors are closely interrelated, and since the "optimum relation" may be expected to be different for different applications and to be affected by extraneous but important practical considerations such as cost, availability, and ease of production, it was clear that a broad program of investigation was required.

NDRC set two aims for itself in undertaking this investigation. The first was to obtain as quickly as possible empirical information concerning the relative effectiveness for night use of the various binoculars that were available immediately or that could be produced readily by slight modification of existing instruments. Binocular testing projects were instituted in which observations were made with a variety of binoculars under controlled laboratory conditions. The object of these testing programs

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was to reveal the design trends that appeared most promising, and to determine the type of instruments that merited field tests under service conditions. The second aim was broader. It was to analyze in greater detail the influence of various factors of binocular design on extending the range of human vision. For this the primary program of binocular testing was expanded to include a variety of experimental instruments, so chosen that the influence of specific factors could be isolated in turn by holding constant all (or most) others. Concurrently, theoretical and experimental analysis of the effects of various factors was attempted in terms of the known physical properties of the instruments and established principles of visual physiology. Ultimately it was hoped to acquire sufficient understanding of the principles governing the utility of binoculars to permit the prediction of the optimum design for any particular application, or at least to narrow the range of possible designs to be selected for final field tests.

The project at Dartmouth was a testing program to determine, for hand-held binoculars, the effect of magnification in increasing the range of visibility at low brightness levels.[1] A more extensive testing program was undertaken at Brown University, where the effects of exit pupil, magnification, and other factors were analyzed, and observations with hand-held and mounted instruments were compared.[2,3] At the University of Pennsylvania, the application of principles of visual physiology to the use of binoculars was studied by the analysis of data from the Dartmouth and Brown testing programs and by specially designed experiments. Particular attention was given to the problem of "unsteadiness of holding" of hand-held instruments.[4] Study of the effects of angular field of view, planned for a later phase of the projects at Brown and Pennsylvania, did not come under consideration before the end of the program. All of the projects were laboratory studies, performed under controlled conditions of observation. No formal program of testing under field conditions was undertaken, as this could be done more profitably after the groundwork in the laboratory. To acquire experience in the use of binoculars under field conditions, however, the contractors and section members participated in a limited number of outdoor tests, particularly those carried out in September and October 1945 at New London by the Bureau of Ordnance.

5.3 OBSERVING CONDITIONS

Visual observation is a task requiring many diverse discriminations and judgments to be made under a wide variety of conditions. Not only must various features of complex visual scenes be discriminated, but the observer must interpret these features in relation to the general situation; the psychological as well as the physical factors are intricate. Experience, skill, and motivation of the observer are of paramount importance. When binoculars are used as a visual aid, skill in handling them must be acquired. The advantages that may be gained by the use of binoculars must be evaluated with proper regard to all these considerations. A scientific approach to the study of these subjects must begin of necessity by simplifying the problems and standardizing the conditions of observation. This is all the more true when the real subject of the investigation is the observer and the use he can make of an instrument, rather than the instrument itself. These restrictions of the problems, essential to sound scientific method, inevitably limit the validity with which conclusions drawn from laboratory experiments can be applied in practical situations.

In the binocular testing programs, efforts were made to preserve as many of the essential conditions of practical observation as was possible without too great sacrifice of scientific control. Where necessary, however, experimental instruments and methods were employed without regard to their immediate practical relevance if they contributed to the ultimate understanding of general principles which operate no less in practice than in the laboratory. The results of these laboratory experiments are thus to be considered as contributing basic understanding and information; the successful evaluation of the utility of binoculars in practice will depend on recognizing the significant factors that distinguish the

practical from the laboratory situation, and on analyzing correctly their effects. It is, therefore, essential to consider in detail the experimental conditions that prevailed throughout the study, pointing out where these conditions agree with those of practical observation with binoculars and in what respect simplifications and limitations have been introduced.

In the first place, no direct account has been taken throughout this study of the effect of the atmosphere on the visibility of objects, either with or without the aid of binoculars. This simplification of the problem is permissible because knowledge of the optical properties of the atmosphere is available from other sources and from this information it is possible to calculate the effect of the atmosphere on the visual appearance of objects.[5] Experiments with binoculars included the study of visibility of targets of reduced contrast. Allowance for atmospheric effects can, therefore, be made by calculation. Such calculations must always be made in the final assessment of the utility of binoculars in practice, although at night the ranges of visibility are usually short and the effects of the atmosphere are often small.

As directed by the project request, the emphasis in this program was on the nighttime use of binoculars. This was an important restriction of the problem, although the range of illumination that had to be investigated was still considerable. Dark clouds or sea backgrounds on a heavily overcast moonless night have brightnesses less than 10 mμL (1 mμL = 10^{-9} Lambert), which is only 10 times the absolute threshold of vision for the average observer (approximately). The range between 100 mμL (clear moonless sky) and 10,000 mμL (moonlight) is of maximum importance; above this brightness level conditions merge with those of twilight, which were not considered in this program. (Studies at twilight brightness levels have been reported.)[6] Except possibly at the very lowest brightness levels, binoculars are useful over this entire range.

Below about 1,000 mμL, the properties of the retinal rods govern seeing (scotopic vision). Such vision is colorless, not very acute, and unable to distinguish small gradations of contrast. Maximal sensitivity is in the peripheral visual field (2 to 20 degrees from the direction of fixation, depending on the brightness level), and seeing requires special skill that can be acquired only by experience. The pupils of the eyes of observers are dilated almost to their maximum. "Night glasses" take advantage of this increased light-gathering power of the dark-adapted eye by providing larger exit pupils than are necessary at higher brightnesses; this is their sole distinction. Although the properties of rod vision dominate at night, brightness levels above 1,000 mμL are of importance; in this range the retinal cones begin to function (photopic vision), superseding the rods. Central vision (foveal) is possible at these levels, acuity and contrast discriminations are higher, and color can be perceived. However, visual capacities are far below the maximum achieved in daylight. Whether dominated by rod or cone function, vision at night is characterized by a strong dependence on the amount of illumination available. This dependence made it necessary to cover the entire range of brightness representing night conditions in the experimental study of binoculars.

In practice, the visual scene is usually very complex. At night, it is true, much of the complexity of the actual scene is not visible. Nevertheless what can be seen by peripheral rod vision is indistinct and seeing is uncertain at low brightness levels. Skill and experience on the part of the observer are required in discriminating one object from another, and in interpreting whether, for example, an object glimpsed is a "target" or only a fleeting shadow or reflection of no significance. In the binocular testing programs, this situation was considerably simplified. The problem was confined to seeing a single small target of high or moderately high contrast against a background of uniform brightness. Seeing an airplane against the sky is an important practical example of this situation. The problem was, furthermore, confined to the simple detection of a target in a known location, or in one of several possible known locations with respect to an orienting mark. Thus the important problems of search and recognition were not included at this stage of the study, and the necessity for discriminating a "real" target from some irrelevant fea-

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ture of the visual scene was eliminated. It is quite possible that these more complicated visual tasks might be differently affected by the use of binoculars than is simple detection, therefore generalizations must be made with caution. Nevertheless, the detection of an object or of a recognizable feature is basic to all these problems, and it is logical to consider it first.

Very simple targets were presented for observation in these studies. Small dark circular spots were caused to appear against a uniformly lighted background. For the most part, targets of high contrast were employed, although enough data on targets of reduced contrast were obtained to cover the range of practical importance. In practice, targets may have irregular shapes and often appear lighter than their background. The laboratory simplifications in these cases, however, are not to be considered as seriously restricting the general applicability of the results, for it is probable that they are of slight importance.[2,4,13,14] It is known that, to a fair degree of approximation, the shape of the target does not affect its visibility at low brightness levels. For given brightnesses of target and background, only the angular area of the target determines whether it will be detected; the shape is unimportant unless the target is greatly elongated in one direction. Many actual targets satisfy this requirement. It is also a good approximate rule that targets of given angular area are equally visible regardless of whether they appear dark against a light background or light against a dark background, provided the absolute value of the brightness difference between target and background is the same. The product of angular area by absolute difference in brightness (incremental flux from the target) is the important quantity governing visibility, and for practical purposes may be treated as a single variable.

Seeing at the threshold of visibility is uncertain. Indeed, the "threshold" is not a sharply defined magnitude, but rather a range of magnitudes within which the probability of seeing varies from zero to unity.[7,8] It has been established that at the absolute threshold of vision less than 10 quanta of light absorbed by the retina are required for seeing a flash of light.[8] Where so few quanta are required, statistical fluctuations will be especially noticeable; the lower the average intensity of the visual stimulus, the less frequent will be the occasions on which the required number of light quanta will be absorbed within a time interval during which excitatory effects in the retina can be integrated. These physical fluctuations of the stimulus are sufficient to account for the uncertainty of seeing at low brightness levels.[8]

The relation between the (average) magnitude of the stimulus and the frequency with which it is seen has considerable practical importance. Knowing it, various problems of threshold seeing can be treated by statistical methods. In some instances in practice, interest may center on seeing at a low level of probability to yield the earliest possible warning of the presence of an object. In other cases, only "practical certainty" is important. Knowledge of the "frequency of seeing" curve permits calculations to be made for any desired level of probability.

The value of a statistical definition of "threshold" has determined the procedure adopted for measuring thresholds experimentally in this study. Observers were allowed a specified period of time in which to examine a given field of view and to report the position of any "target" they saw. A number of such presentations at constant background brightness were made with the magnitude of the visual stimulus (size of target) varied in discrete steps covering the range from zero frequency of seeing to 100 per cent seeing.[b] Enough observations were obtained to permit a moderately reliable estimate of the frequency with which each size of target could be seen over the range necessary to yield the entire "frequency of seeing" curve for each experimental condition. Typical "ogives" obtained in this way are reproduced in the Dartmouth final report.[1] The supplement to the Brown final re-

[b] This method of determining threshold has been termed the "method of constant stimuli" in the literature of psychophysics. That this is a glaring misnomer when applied to visual stimuli at low brightness levels is evident from what has been said concerning the origin of the uncertainty of seeing near the absolute threshold of vision.

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port[3] contains tabulations of the original data, from which the ogives may be reconstructed.

For most practical purposes it is convenient to define the "threshold" as the target size that can be detected with a frequency of 50 per cent. At Dartmouth, the 90 per cent level of frequency of detection was also considered in the final report. At Brown, separate experiments were performed to establish the important fact that the shape and slope (on a logarithmic scale) of the "frequency of seeing" curve was practically independent of the conditions of observation, within the limits of the experiments. A single parameter (the target size for 50 per cent detection) was, therefore, sufficient for the comparison of visual performance under various conditions. In the experiments at the University of Pennsylvania similar procedures were adopted. Target brightness was sometimes varied instead of target size in determining the threshold; these alternatives are essentially equivalent for practical purposes.

The criterion of detection that was used was based upon the observer's ability to report the position of the observed target correctly. Targets were caused to appear in one of several possible positions with respect to a centrally located orientation mark that was easily visible. The observers soon became familiar with the situation and knew where to look for possible targets. With the exception of a few special experiments a target was always present in some one of the positions. Consequently a certain number of reports would be correct by pure chance even if the observer were only guessing, and actually saw no target at all. It was necessary, therefore, to apply a "correction for guessing" to determine the true frequency of detection for each level of stimulus magnitude. The details of this statistical procedure are given in the final reports.

The restrictions and simplifications of these laboratory observations and the considerations of "frequency of seeing," "correction for guessing," etc., seem at first artificial and far removed from problems of practical seeing. Such is not entirely the case. Essentially the same problems are actually present in practice; they are merely unrecognized. In viewing any visual field, the observer must always answer for himself the question: "Do I see an object?" Uncertainty may exist, and the observer must then perform for himself a short "frequency of seeing" experiment to decide whether a suspicious sensation of light or shadow is real or spurious. Only the uninitiated think that seeing at threshold levels is a simple matter of clear-cut presence or absence of a visual sensation. In practice, it is true, the observer cannot compare a restricted number of locations to determine which of them contains the target. Targets may be present in an infinite number of positions, or not at all. The skilled observer examines a field systematically, often assuming that a target is present unless he fails to obtain a reasonably reliable visual confirmation. The use of an orientation mark in the laboratory experiments is not entirely alien to practice. Easily visible features of a visual scene are customarily utilized by skilled observers as orientation marks in searching the field systematically. When such features are not present, systematic observation is much more difficult and less trustworthy. Situations do arise in practice where no such features are visible, as when scanning the sky with binoculars; these the laboratory experiments fail to represent.

Conditions of observation in the laboratory are, of course, greatly idealized as compared to field conditions. This is necessary in well controlled experiments, although the hardships and diverse circumstances of practice have a decisive bearing on the ultimate utility of binoculars. Effects of wind, vibration, and movements of the observing platform were deliberately avoided in the basic laboratory experiments; their effects on the use of binoculars in practice may be very great. Toward the end of the program, a few observations were made at Brown with a rolling platform (Scoresby machine), and comparison was made between hand-held and alidade-mounted instruments. Measurements of angular vibration and unsteadiness of hand-held binoculars on shipboard were made by the Pennsylvania group.

The selection of observers to take part in the laboratory tests was made with care. An effort was made to parallel the Service requirements of age and physical vigor; visual requirements were similar. A large proportion of women was

employed as observers at Brown. There is no reason to believe that their visual performance is different from that of men; if anything, they tend to be more patient and conscientious in a tedious laboratory experiment. A careful period of training was required for each observer before data were collected. Unreliable performance and failure to develop skill during this initial training period was cause for rejection, as was failure to show a conscientious attitude. Discomfort and fatigue were, of course, avoided as much as possible in the laboratory experiments; boredom was unavoidable.

In practice, the situation in these respects varies widely. The laboratory conditions might be considered analogous to the most favorable conditions of practical observation, except that motivation is doubtless greater where the stakes are higher. Insufficient or incorrect training and failure to select reliable observers are all too common in practice. In military service, discomfort and fatigue may be excessive at times. Boredom is relieved only when there is an element of danger. It would be grossly incorrect to fail to take into account such elements in assessing the ultimate practical utility of binoculars.

The binoculars that were used in these studies were high-quality instruments, either standard Navy equipment or carefully designed modifications of them. Special objectives or special oculars were manufactured to yield instruments with the desired magnification and exit pupil. The objectives were diaphragmed in some experiments to provide the exact values of exit pupil required. All optical surfaces were coated with a low-reflection film (lithium fluoride). The transmission of the instruments was between 70 and 80 per cent. Great care was exercised in the laboratory experiments to have the binoculars correctly adjusted for each individual observer. The correct setting of the binocular for interpupillary separation was made carefully in every experimental session. The optimum focus was determined by experiment for each observer who then set the instrument he used at this value in every test. Such precautions are at least possible in practice even though they are not always taken.

The discussion of these factors affecting observation serves as more than a delineation between practical and laboratory conditions. Recognition of elements unfavorable to observation in practice can lead to their elimination in some cases. Ability to deal systematically with various perceptual aspects of seeing marks the difference between a skilled and unskilled observer. Recognition of elements that contribute to skill can lead to improvement in training procedures. The experimental precautions, the systematizing, and the simplifications that have been found necessary to obtain reliable results in the laboratory thus contribute to the understanding and solution of practical problems.

5.4 EXPERIMENTAL PROJECTS

5.4.1 Binocular Testing Program at Dartmouth College

EQUIPMENT AND METHODS

The testing program at Dartmouth College[1] dealt with the comparative effectiveness of binoculars of various magnifications, all possessing a 5-mm exit pupil. The binoculars employed were 6x30, 7x35 (a standard 7x50 with objective diaphragmed to 35 mm), 8x40, and 10x50. The experiments were conducted in an indoor observing range, in which a white screen (12x12 ft) was placed 60 ft from an observing station and illuminated uniformly at the desired level.

The brightness levels chosen were 40, 400, 4,000, and 40,000 mμL. They were adjusted with the aid of a University of Rochester *sky photometer*. The original calibration of this instrument, and a later verification at Pennsylvania, were based on a tungsten standard having a color temperature of 2360 K, standardized at a high brightness level by conventional photometry, and attenuated physically to the low levels required. This is in accordance with the specification for low-brightness photometry proposed by the American Standards Association. The same specification was adopted at Brown and at Pennsylvania.

The "targets" were circular holes in the

screen, and appeared black (100 per cent contrast) against the dimly lit background. They could be made to appear in any one of four possible positions equally spaced in a circle subtending an angular radius of 0.7 degrees about a weak red fixation spot at the center of the screen. Six different target sizes were used for each set of brightness and magnification conditions.

Three full-time observers were employed, after a preliminary period of training. They were dark-adapted for 45 min before each experimental session. For each observation, a warning signal was given, and the observers were allowed 6 sec to look. At the end of this time they signaled the position in which they saw the target. They were not forced to guess if they could not see the target. The observers stood to make the observations, and held the binoculars in their hands without resting them on any solid support.

For each target presentation, the actual position of the target was recorded, and also the position reported by each of the observers. The correct responses could thus be noted and the errors analyzed.

In any experiment of this kind a certain number of errors will be made in reporting target position, even with observers trained to do their best conscientiously, and even if the observer is not forced to guess. Indeed, failure to make any errors is evidence that the observer is being too cautious; this will cause him to miss targets that are merely a trifle uncertain. Presence of errors means that the observer is "playing his hunches," doing a certain amount of guessing of his own accord, and presumably working at the very lowest limit possible for him. Since a target was always present in some one of the four positions in these experiments, there was one chance in four that any guess made would be correct, even though the observer did not actually see the target. It is desirable to make allowance for these fortuitously correct guesses, for in practice, targets can appear in an infinite number of positions, and no appreciable number of lucky guesses will occur. The necessary allowance for guessing can be made from the number of incorrect responses that were recorded, for on the basis of pure chance these must constitute three-fourths of the total number of guesses. One-third of the number of incorrect reports, therefore, equals, on the average, the number of reports that were correct guesses. This number subtracted from the total number of correct reports yields the best estimate of the number of observations in which the target was "actually" seen. The number actually seen, for any given target size, divided by the total number of presentations of targets of this size, gives the "probability of detection," corrected for guessing, for this size of target.

In the analysis of the Dartmouth data by Section 16.1 it was found that these considerations were complicated by the fact that the incorrect reports tended to favor those positions adjacent (on the circle about the fixation point) to the true position of the targets, as though the observer was "almost right" in some cases. The incorrect reports which gave the position diametrically opposite to the actual target position were, therefore, considered to give a truer estimate of guessing. The discussion of the final method of analysis of the Dartmouth data is given in the appendix to the final report.[1] For a discussion of "frequency of seeing" and the general problems of determining threshold by this method, the report CAM No. 110 may be consulted.[7]

Results

Figure 1 exemplifies the way in which the data collected at Dartmouth were presented, after the correction for guessing had been applied. These curves (ogives) show the relation between probability of detection and size of target for the four binoculars studied and for naked-eye observations. This set of curves was obtained from observer B for black circular targets at a screen brightness of 40 $m\mu L$. Similar sets were prepared for other screen brightnesses and for the other observers. Figure 1 shows that smaller targets could be detected with binoculars than could be seen by the naked eye. In general, the higher the magnification the more was the "frequency of seeing" curve displaced in the direction of smaller target sizes (in the particular case of Figure 1, the $7\times$ and $8\times$ ogives constitute an exception).

If some arbitrary level of probability of detection is chosen as defining "threshold," the target sizes required to meet this criterion may be read from these graphs. This was done for the various cases, and the thresholds of the three observers averaged to obtain a mean threshold for each magnification and brightness level. The results are given in Table 1, for a 50 per cent level of detection, and for a 90 per cent level (corrected for guessing). The data in this table are presented in terms of "relative range." (The relative range is the reciprocal of computation, the smaller ranges in the 1× column being the expression of the decreased acuity of vision caused by the brightness losses of the instrument. If brightness loss were the only factor affecting observation through binoculars, the observed ranges obtained with any particular binocular should agree with the ranges calculated by multiplying the "1×" ranges by the magnification of the instrument. This expectation is met with a fair degree of approximation, as may be seen by inspection of Table 1. Figure 2 presents these data (for 50

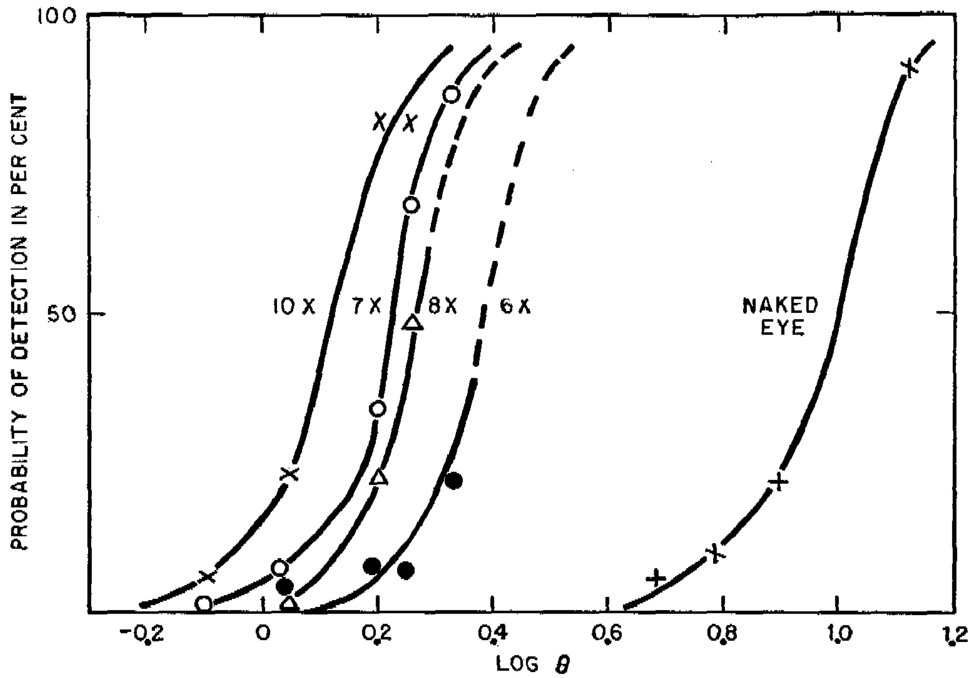

FIGURE 1. Curves relating probability of detection (corrected for guessing) with target diameter (θ, in milliradians), for naked-eye observations and for observations with binoculars of various magnification (6×, 7×, 8× and 10×, all having 5-mm exit pupils). (Dartmouth College results.)

the angular diameter of the threshold target in radians.)

The threshold ranges obtained from naked-eye observation (for two of the three observers) are entered in Table 1 in the column headed "N. E." In the next column, headed "1×" are hypothetical ranges computed for observers using a binocular of unit magnification having an exit pupil the same size (5 mm) as that of the binoculars actually used, and a transmission equal to the average of the transmissions of the actual instruments. The naked-eye observations furnished the basis of this per cent probability of detection) in graphical form. It shows the linear increase of range of detection with magnification. Solid lines connect the observed points, the lowest point for each curve (plotted at $M = 1$) is the value for naked-eye observations at that brightness level (column "N. E."). The dotted lines show the relation predicted from the "1×" ranges multiplied by magnification (column "1×"). Figure 2 shows a slight lack of agreement between observed and predicted ranges at the highest brightness level, and also at the highest magnification. Moreover, the values for the 7× in-

[redacted]

strument seem to be consistently better than predicted, and somewhat out of line with the rest of the observations. However, analysis of the results shows that these discrepancies are only on the borderline of statistical significance.

The principal result of the Dartmouth studies, and the one that is of practical importance, is that the use of binoculars greatly increases the range of detection of small targets at night, and that this advantage is greater, the higher the magnification, at all brightness levels and at all levels of probability of detection. This holds true for magnifications up to 10×, and shows no sign of falling off at this value. The results indicate that consideration should be given to the use of higher magnification for hand-held binoculars than was customary in practice. This general result was confirmed by subsequent studies.

TABLE 1. Relative ranges of detection for black circular targets viewed against backgrounds of various brightnesses with binoculars of various magnifications (5-mm exit pupils). (Dartmouth College results.)

Data are given for two levels of probability of detection, corrected for guessing [$P_c(d)$]. "Relative range" is the distance (d) at which a target of unit diameter is detected with a probability $P_c(d)$. Naked-eye ranges (N.E.) are included, obtained by 2 of the 3 observers. The column headed "1×" contains ranges interpolated from N.E. observations at different brightness for a hypothetical binocular of unit magnification, having a 5-mm exit pupil and a transmission equivalent to the average of the actual instruments used.

Background brightness mμL	N.E.	1×	6×	7×	8×	10×	
40	120	87	580	705	625	750	
400	190	160	935	1,150	1,340	1,540	$P_c(d)$
4,000	390	294	1,710	2,420	2,160	2,880	$= 50\%$
40,000	1,100	759	3,580	5,110	4,770	6,660	
40	95	74	410	480	460	565	
400	130	120	705	895	1,010	1,130	$P_c(d)$
4,000	300	220	1,360	1,730	1,660	1,860	$= 90\%$
40,000	850	590	2,720	3,440	3,020	3,570	

The detailed relation between magnification and range of detection is of considerable theoretical, and ultimately practical, interest. In the Dartmouth results the observed ranges agreed with those predicted on the basis of magnification alone, after allowance for simple brightness losses caused by physical loss of light transmitted by the instrument, and by an exit pupil smaller in size than the natural pupil of the observer's eye. This means that in the Dartmouth studies the observations were not affected by misalignment of the binoculars with the observer's eyes or by tremor movements of the binocular image caused by unsteady holding. It is difficult to believe that these factors are without effect in practice, and it is somewhat surprising to find them without effect even in laboratory experiments. The other experimental studies at Brown and at Pennsylvania failed to confirm this particular conclusion drawn from the Dartmouth results.

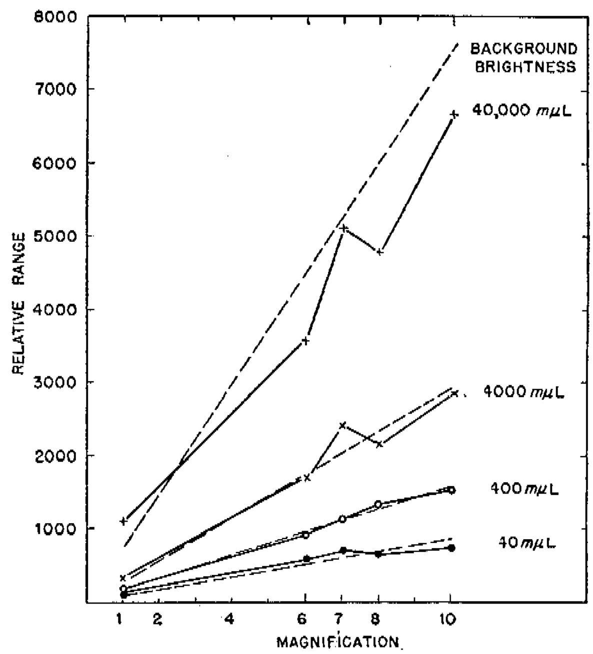

FIGURE 2. Relative ranges at which circular black targets were detected with a probability of 50 per cent with the aid of binoculars of various magnifications (5-mm exit pupils), at 4 levels of background brightness. Data from Table 1. (Dartmouth College results.)

5.4.2 Binocular Testing Program at Brown University

EQUIPMENT AND METHODS

The testing program at Brown[2] was essentially similar to that at Dartmouth, but was

[redacted]

larger in its scope. More observers were employed, and a wider variety of experiments was undertaken.

An observing range was constructed, capable of being darkened completely. A white matte screen was placed 70 ft from the observing station at which observation booths were constructed to accommodate six observers at one time. A Leitz VIII-S projection lantern was used to project dark circular targets from 2-in.

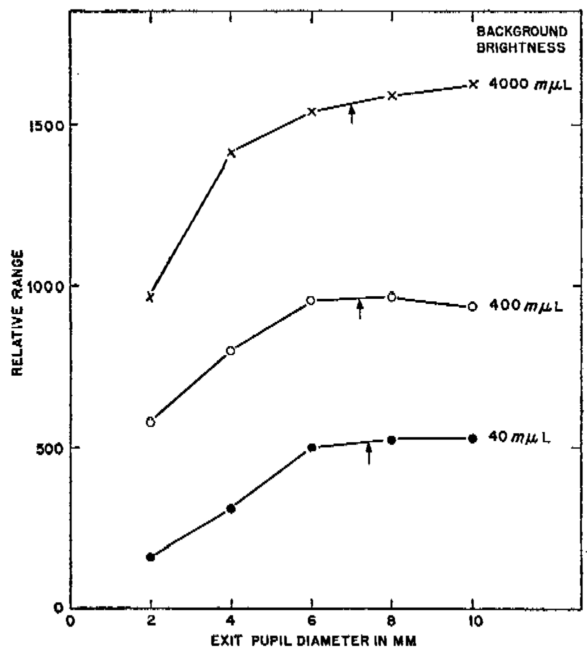

FIGURE 3. Relation between relative range and exit pupil diameter for 5× binoculars, at three levels of background brightness. Arrows indicate the average diameter of the natural pupil at the respective brightness levels. The relative ranges for naked-eye observations were 280, 320, and 630 for 40 mμL, 400 mμL, and 4000 mμL respectively. (Brown University results.)

square glass slides onto the screen. Screen brightness was varied, and controlled photometrically, over a range from 4 mμL to 12,600 mμL. The low brightness photometer used was constructed at the University of Pennsylvania (described in final report of Contract OEMcmr-209)[4] and standardized in accordance with the American Standards Association for low brightness photometry. The photometry at Dartmouth, Brown, and Pennsylvania was thus in agreement.

The contrast of the targets (in absolute values) could be varied from the maximum obtainable with the projector (close to 100 per cent) to any lower value. Data thus obtained could be used in computing the effects of different atmospheric conditions.

The targets were caused to appear in any one of six possible positions equally spaced on a circle subtending an angular radius of 3 degrees about a central orientation mark. For any given experimental session (particular binocular, particular background brightness), target sizes were selected to cover the entire range of frequency of detection, and presented in random order in various positions, also taken in random order. In each observing booth was a push-button panel used by the observer to indicate the position in which the target was seen. The recorded responses were transferred to punchcards for convenient computation.

As in the Dartmouth experiments, a "correction for guessing" must be applied to restore the situation to a practical status where guessing has a negligibly small chance of success. In these experiments there were six possible target positions, but since target positions were never repeated in any one "run," one-fourth rather than one-fifth the number of incorrect responses was taken as the estimate of the number of guesses that were correct by chance. No analysis of the errors was made, as was done at Dartmouth. Presumably the greater angular separation of the targets (3 degrees, instead of 1 degree as at Dartmouth) would decrease the possibility of error from this source.

The observers were recruited from the undergraduate students of Brown University and Pembroke College. They were carefully selected and trained; altogether approximately sixty were employed.

It is difficult in a brief summary to convey an adequate impression of the amount of thought and effort that went into these binocular testing programs, and to the significance of the details of method and procedure. The very fact that reliable measurements could be made of observer performance with binoculars is one of the results of this general program of study. The precautions and controls that were necessary to accomplish this furnish insight into the factors affecting the use of binoculars.

[redacted]

Many of the same factors requiring control in these laboratory studies are important in practical observation. The original contractors' reports may profitably be read with practical problems kept in mind.

Results

Exit Pupil Series. The first set of experiments undertaken at Brown was the comparison of instruments with various exit pupil sizes, all of the same magnification (5×). The experimental instruments were identical (5x50), except that the objectives were diaphragmed, giving exit pupil diameters of 2, 4, 6, 8, and 10 mm. Observations were made at three levels of background brightness; the results are shown in Figure 3. This figure shows the unmistakable advantage of increasing the aperture of the instrument so that its exit pupil makes fuller use of the observer's expanded pupil at low brightness levels. In detail, however, the results are somewhat disappointing, for they show negligible improvement in range when the exit pupil is increased beyond 6 mm. The natural pupils of observers adapted to these low brightness levels are on the average considerably greater in diameter than 6 mm. Direct measurements by infrared photography of the pupil diameters of the Brown observers were made by the group at Pennsylvania. These showed that the average pupil diameter for the range of brightness of these experiments was approximately 7 mm. It is not easy to understand why the improvement in range noted in Figure 3 below 6 mm does not continue up to at least 7 mm.

Magnification Series. A second extensive series of experiments concerned the effect of increasing magnification of binoculars having the same objective diameter. In such instruments the increased advantage from greater magnification would be expected to be offset partially by the effects of decreased exit pupil diameter. The set of instruments was prepared by altering the eyepieces of standard 7x50 binoculars so that the shape and weight and balance of the various instruments were the same. In planning this experiment it was felt that, if the results indicated a definite optimum magnification other than the standard 7×, comparatively slight changes in the design of the standard instrument, involving only the eyepiece, could be made to yield a profitable improvement in practice.

The results of this series of experiments are given in Table 2, and in Figure 4. In the table, the results are given in terms of "binocular gain," which is the factor by which the naked-eye range of detection is to be multiplied to yield the range of detection afforded by the binocular. Under ideal conditions, this would equal the magnifying power of the instrument.

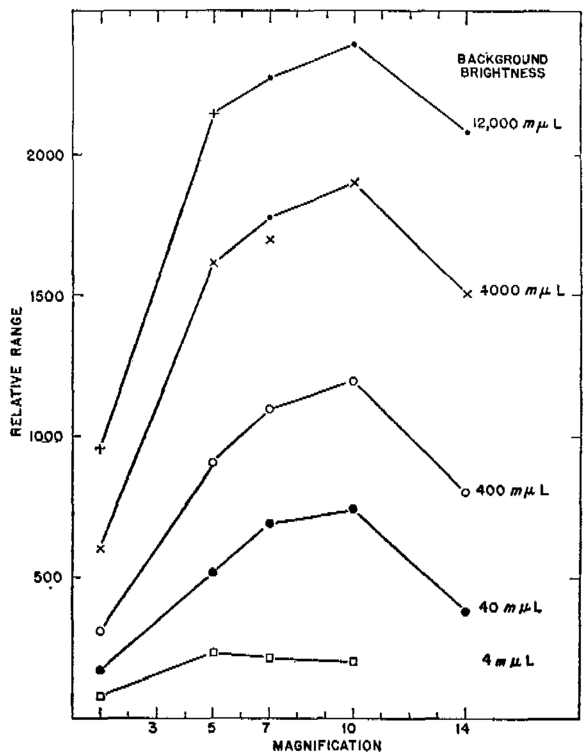

FIGURE 4. Relation between relative range and magnification at various levels of background brightness, for binoculars with 50-mm objectives. Naked-eye observations are plotted at M 1. (Small dots at the breaks of the two uppermost curves give values interpolated from Figure 20, OSRD Report 6128.)[2] (Brown University results.)

Because of loss of brightness of the image resulting from physical loss of light, combined with failure of the instrument's exit pupil to utilize the full aperture of the observer's eye, the "ideal" gain cannot be expected. Allowance can be made for the loss in range from these simple causes. The resulting "theoretical gain"

is given in the bottom row of Table 2. The most striking feature of these results is the very serious failure of the observed binocular gains to measure up to the values that may be expected. Evidently there are additional factors that affect the results besides the simple brightness losses that have been considered. These results of the Brown studies are thus at marked variance with findings at Dartmouth, and no certain explanation has been found for this discrepancy.

The results show a maximum in the relation

TABLE 2. Binocular gains at various levels of background brightness, for binoculars of various magnifications (50-mm objective diameter). (Brown University results.)

"Binocular gain" is the range at which a target can be detected with the aid of a binocular divided by the range at which it can be detected with the naked eye, all other conditions remaining the same.

Background brightness mμL	5x50	7x50	10x50	14x50
4	2.9	2.7	2.6	...
40	3.1	4.1	4.5	2.3
400	3.1	3.7	4.1	2.7
4,000	2.7	2.8	3.2	2.5
"Theoretical gain" (see text)	4.1	5.8	7.2	7.8

between binocular gain and magnification in this series where the objective aperture was held constant. This maximum is at 10× at all brightness levels except the lowest (4 mμL). The 7× binoculars gave gains that were slightly, but significantly, lower. The gains obtained with the 14× instrument were definitely lower. This may have been partly due to the reduced eye relief which is inevitable with higher power, and partly to the reduced field of view which made it more difficult to examine the six target locations efficiently in a specified time interval. Eyepieces with somewhat increased eye relief were supplied by the Perkin-Elmer Corporation. It seems unlikely, however, that further improvements would make it possible for 14x50 binoculars to equal the performance of well-designed 10x50's.

A similar series of experiments was performed with instruments of 70-mm objective aperture and various magnifications. The results obtained were of the same general character as for the 50-mm series. After making allowance for observer differences, it was concluded that the ranges with the 70-mm instruments were approximately 5 per cent greater than with the analogous 50-mm instruments. This disappointing meager return is less than is to be expected from elementary theoretical considerations, but is in keeping with the findings of the exit pupil study where increases in pupil diameter above 5 mm gave disappointingly small increases in the range of visibility.

The foregoing results were all obtained with targets of high contrast (approximately 100 per cent); in practice, target silhouettes are often of low contrast. In addition, an important effect of the atmosphere is to reduce the apparent contrast of objects. For these reasons, experiments were conducted with targets of reduced contrast. According to simplified theory the threshold of visibility of a target, as has already been noted, is determined at any given level of background brightness only by the product of angular area of the target by the absolute difference in brightness between target and background. The latter is proportional to the target contrast (at any fixed background level); the former varies inversely with the square of the distance to the target. Hence the "threshold range" should vary in proportion to the square root of the contrast. This was borne out by the experimental results, for contrasts greater than 50 per cent. For targets of lower contrast the observed ranges were materially less than predicted by this simple relation, and presumably must be treated by more exact theoretical analysis. There was some evidence that the loss in range for low-contrast targets was less for binoculars than for naked-eye observations. For the details of these findings, the Brown final report[2] must be consulted.

When the relative range is plotted against background brightness for various instruments of the 50-mm series, the graphs are quite accurately linear in most cases. These relations combined with the simple law governing the effect of contrast on target visibility make it possible to express the Brown results (for the 50-mm series) by empirical equations which form a

[redacted]

convenient condensation of the observational data:

Naked Eye	$\log R = 0.275\ (\ 6.49 + \log B) + \frac{1}{2} \log C$
5x50	$\log R = 0.247\ (\ 9.4\ + \log B) + \frac{1}{2} \log C$
7x50	$\log R = 0.205\ (12.25 + \log B) + \frac{1}{2} \log C$
10x50	$\log R = 0.195\ (13.19 + \log B) + \frac{1}{2} \log C$
14x50	$\log R = 0.280\ (\ 7.75 + \log B) + \frac{1}{2} \log C$

Additional Experiments. The project at Brown University succeeded in its primary purpose of providing a large number of reliable data on the effects of fundamental features of binocular design on the detection of targets at low brightness levels. In addition, numerous other minor problems were attacked, of interest both for their significance in practical observation and for their bearing on the question of why binoculars fail to come up to expectations. The Brown final report[2] summarizes the results of these parts of the projects:

> The effects of unsteadiness in holding the binocular were investigated by a series of observations in which the binoculars were mounted in standard Navy alidades. The results showed an average gain in range from alidade mounting of about 8%. These experiments cannot be considered, however, as completely eliminating the tremor effects, since the observer was still required to move the binocular about in scanning the field. Furthermore, little benefit could be expected from the alidades in diminishing the tremors of head and eye. Specially designed head-rests ["eye-guards"] for holding the eyes in a fixed position with respect to the binocular, thus reducing the relative motion of the eye and the instrument, were also tested. The results of this study failed, however, to show any gain in range under laboratory conditions (absence of wind and ship vibration).
>
> It was particularly desirable to determine the effect on detection of angular motions such as those experienced on shipboard. This problem was studied by seating an observer in a moving Scoresby machine during target observations. The results indicate a rather remarkable postural adaptation on the part of the observer, since no definite loss in range was detected for periods of oscillation greater than 12 seconds even when accompanied by an angular motion of 14°. For a 9-12 second period having the same amplitude the range was decreased on the average by 15%.
>
> Since certain other night vision studies had been carried through with target presentations much shorter than the 30-second period which was adhered to in the present program, it seemed desirable to make a series of comparative studies between the ranges obtained with 30-sec. and 6-sec. exposures. . . . Both naked-eye and binocular ranges were less, as might be anticipated, for the 6-sec. period, but in general the deficit in range with binoculars was somewhat greater than with the naked eye, thus leading to slightly lower binocular gain. Earlier studies had shown that little, if anything, was to be gained by exposures longer than 30 sec.
>
> Still another conceivable cause for low binocular gain lay in a possible lack of perfect coordination between the two eyes when using binoculars. In order to explore this possibility, a series of comparisons was made between the ranges attained with a single eye and the two eyes acting together. The results show a relative advantage for the two eyes over a single eye with naked-eye observations of between 19% and 26%, whereas the corresponding advantage when binoculars are used is less than 15%. The difference may possibly be due to a greater difficulty with clipping when the two exit pupils of the instrument are to be simultaneously aligned with the pupils of the two eyes.

Commenting on the results of the entire project, the final report makes this interesting statement:

> Perhaps the most striking feature of the results obtained is the minor extent to which variations in binocular design affect performance. Thus, increasing the exit pupil from 5 mm. to 10 mm. leads to much lower gains than might be anticipated. Similarly, increases in binocular power do not yield the full returns which might be hoped for, particularly at the highest and lowest intensities of illumination. Furthermore, the benefit which accrues from alidade mounting would appear to be much less than might be anticipated. . . .

The maximum ranges that could be obtained at low levels of illumination were given by the 10x50 and 10x70 binoculars mounted on alidades. These ranges exceeded those given by hand-held standard 7x50 binoculars by only about 15 per cent.

This result should not minimize the importance of improvements in the design of binoculars. That these advantages do not come up to expectations must not be allowed to obscure the fact that all good design features of binoculars contribute to good performance. A large exit pupil is better than a small one at night; alidade mounting aids observation with binoculars; a binocular instrument is better than a monocular. Particularly noteworthy are the effects of magnification: Under laboratory conditions, the range of visibility at night is increased by increasing the magnification of a constant-aperture binocular, up to 10×. The fact that each of the various features of binocular design contributes disappointingly small returns is all the more reason for giving close

attention to all the details, since when taken together these add up to yield important advantages in observation.

5.4.3 Investigations at the University of Pennsylvania

The project at the University of Pennsylvania[4] was set up apart from the specific programs of binocular testing to permit an experimental analysis of the factors affecting visibility through binoculars. It was hoped by such a study to acquire an understanding that would ultimately make it possible to predict the effects of design features not specifically considered in the testing programs, and that would make future exhaustive testing projects unnecessary for every new type of binocular developed or for every new set of Service demands. This is an ambitious hope for a problem that is essentially concerned with the human observer. Nevertheless such an aim is essential if the entire project is to have any significance beyond the specific results obtained with particular instruments and particular observers.

This aim, of course, was by no means lacking from the testing projects at Dartmouth and Brown; but these were primarily concerned with providing results that could be interpreted directly in practice, and were often unable to go into the analysis of factors that were difficult to understand. The final report of the Brown project[2] goes into many questions of interpretation; the discussion of these will be included after the description of the results from Pennsylvania.

At the University of Pennsylvania an effort was made to correlate known facts of visual physiology with the findings of the binocular testing programs at Dartmouth and Brown and to conduct experimental studies as needed to clarify understanding of these findings.

Studies of Pupil Size

It was evident from the beginning that accurate information was required concerning the size of the natural pupil of the human eye, both as it is affected by the brightness of the external surroundings to which the observer is adapted, and as it varies from individual to individual and from moment to moment in each individual. It was also necessary to have accurate knowledge of the contributions of all areas of the pupil to the total apparent brightness of the retinal image. The first project undertaken at Pennsylvania was, therefore, to survey the literature on the pupil, and to add experimental knowledge where necessary.[9]

It is known that at high brightness levels light passing through the margins of the pupil is not so effective in producing a sensation of brightness as light passing through its center (Stiles-Crawford effect). This is perhaps the result of a directional property of the retinal cones which may admit light only within a limited entrance angle. The original papers on this subject report that this effect is not present for the rods, i.e., for rod vision; all areas of the pupil are equally effective. A survey of the literature[4] on this subject indicated that this conclusion was amply verified by competent workers. Therefore, for most brightness levels at night, where rod vision only is concerned, one may consider the effective brightness of the retinal image to be proportional to the area of the pupil that is utilized by the binoculars. Only at the highest levels of brightness that were investigated in these projects, where cone vision begins to be of importance, is it perhaps necessary to take into account the Stiles-Crawford effect.

A number of careful studies have been made of the size of the pupil as a function of the brightness level to which the eye is adapted. However, all of these taken together include only a few subjects; it was felt necessary that a short survey be undertaken to gain some accurate knowledge of the variations to be expected in large numbers of people. The experimental study[9] of the pupil that was undertaken at the University of Pennsylvania employed the usual method of infrared photography. The subjects first measured were ten observers from the Brown University project. Fortunately, it was not necessary to devote as much effort to this survey as had been anticipated, for a British report[10] became available in which was presented the exact information that was desired. The measurements performed on the

ten observers at Brown provided useful confirmation of the British data, in addition to furnishing pupil data for specific subjects concerned in the binocular testing project. A further result of this study was the finding that fluctuations in pupil size, from moment to moment and from day to day in a given individual, while present, are not large enough to have any bearing on the present problems. It was also concluded that while accommodation affects pupil size, the slight amount that most observers exert when using binoculars at night will have no significant effect on pupil size.

An analysis of the British data is included in the report on the pupil survey. It was found that expressing the pupil size either in terms of diameter or area resulted in a distribution that was fitted satisfactorily by the normal error function. The distribution of areas, however, resulted in standard deviations that were nearly the same for all brightness levels, and hence this is a convenient presentation for purposes of computation. These valuable data from the British report[10] are reproduced in Table 3,

TABLE 3. Average area of the pupil of the human eye, at different low levels of brightness adaptation. (From OSRD report No. 6098.)

Mean areas for a sample of the population (52 subjects), and standard deviations of the distributions; measurements from British report A.R.L./N.2/0.502. (1942).[10]

Adaptation brightness (candles/sq ft*)	Mean pupil area (mm^2)	σ (mm^2)
0	43.86	9.33
1×10^{-6}	43.61	9.23
1×10^{-5}	41.81	9.13
1×10^{-4}	39.50	9.45
1×10^{-3}	38.27	9.04
1×10^{-2}	34.34	9.77

* 1 candle/sq ft = 3.36 millilamberts.

which gives the values of the mean pupil area at each of five brightness levels, with the corresponding values of standard deviation. For convenience, Table 4 presents the pupil diameters for various brightness levels in mμL, calculated from the mean areas interpolated from the data of Table 3.

These data on the size and variability of the natural pupil of the eye have been used in calculations concerning the choice of exit pupil size for night binoculars.[11] Only those observers whose pupils exceed a specified diameter will profit by an increase in the size of the exit pupils of binoculars above this value. Therefore, increases in exit pupil size above the size of the smallest human pupil (about 5 mm) yield diminishing returns. Quantitative calculations have been made, based on the observed distribution in size of the human pupil, which yield the visual information on which choice of exit pupil size can be based. It is to be noted that the actual measurements made at Brown on the effect of exit pupil (see Figure 3) show an even smaller advantage from large exit pupil size than these calculations would allow one to expect.

TABLE 4. Diameters of pupils of average area, for various levels of brightness adaptation. (Interpolated from British data.)

Adaptation brightness (mμL)	Diameter (mm)
Dark	7.46
10	7.40
100	7.20
1,000	7.04
10,000	6.48

The size and variability of the human pupil likewise has a bearing on the effects of errors in the interpupillary setting of binoculars.[12] Such errors cause one or the other, or both, of the telescopes to be misaligned slightly, and this leads to brightness losses which somewhat reduce the advantage that a binocular instrument possesses over a monocular. This is true only for cases in which the exit pupil of the instrument is exactly the same size as the observer's pupil, otherwise a certain amount of error in interpupillary setting can be tolerated without brightness loss to either eye. Calculations of the net effect of this error, and its bearing on the design of instruments with fixed interpupillary settings, are presented in the article cited.

ANALYSIS OF DARTMOUTH RESULTS

It was a primary purpose of the project at Pennsylvania to determine to what extent ob-

servations with binoculars could be explained in terms of known physical and physiological principles. It was expected that the effects of unsteadiness of holding would appear as discrepancies between the ranges of target visibility actually observed with various instruments and those calculated from naked-eye observations, making allowance for simple brightness losses. These effects would then be subjected to whatever experimental analysis seemed appropriate.

When the results of the Dartmouth tests became available, they were analyzed in terms of known principles of visual physiology.[13] Since naked-eye data obtained at Dartmouth were very sparse, a report from the University of Rochester[14] was utilized to supplement the Dartmouth data. This report furnished data on the naked-eye visibility of targets, relating target size, target brightness, and background brightness at low levels of illumination. Analysis showed that the visibility of a target was determined by the product of its angular area and the brightness difference between it and its background. For a given level of background brightness, this total flux added (or subtracted) by the target was approximately constant for all values of target size below 10^{-4} steradians. It was the same for a dark target viewed against a bright background as for a target that appeared brighter than its background. The threshold flux increment contributed by the target varied in a regular way with the background brightness, increasing slowly from the basic value set by the threshold flux from a point source seen against a completely dark background to somewhat more than 10 times this value at approximately 0.5 μL. Over this part of the brightness range, the Rochester data could be described by Hecht's treatment of brightness discrimination.[15] At 0.5 μL the data showed a break, an effect explained by the transition from rod to cone vision, and the increase of threshold flux increment with background brightness was less rapid than at lower levels. The Rochester data thus furnished a basis for computing the threshold size of a target of any contrast seen against a background of any given brightness within the range covering night conditions. The Dartmouth naked-eye observations were found to agree well with these Rochester data.

To apply this treatment to the observations with binoculars it is necessary to consider the limiting pupillary aperture. It is convenient to convert all of the values for background brightness, for both naked-eye and binocular observations, into terms of relative "retinal illumination." This was done by multiplying all brightnesses by the area of the limiting aperture—natural pupil or exit pupil, whichever was smaller. Treated in this manner, and after allowing for the magnification and transmission of the binoculars, it was found that the Dartmouth binocular data were in good agreement with the naked-eye data. The points for all the instruments, 6×, 7×, 8×, and 10×, at the four brightness levels used clustered about the same curve relating threshold flux increment to background brightness that described both the Rochester and Dartmouth naked-eye data. In other words, the simple brightness losses caused by the instruments were sufficient to explain the visibility of the magnified target images seen through the binoculars. No residual effects of unsteady holding remained to be explained.

The treatment just outlined is given in detail in the interim report[13] cited, and also in the Dartmouth final report.[1] It is the basis on which the straight lines of Figure 2 were drawn, showing that the observations with binoculars agreed with the "expected" values. This result was rather surprising, since it was believed generally that unsteady holding caused large losses in the efficiency of hand-held instruments, particularly at high magnifications. The skepticism concerning this conclusion, expressed in the interim report cited, was justified, for the results presented in a British report on binocular studies[16] and the results of the Brown studies[2,3] when they became available showed unmistakably that the simple conclusion drawn from the analysis of the Dartmouth data was open to question. The reason for the discrepancy is not clear; it may be noted, however, that the visibility ranges observed with binoculars at Dartmouth were in reasonably good agreement with those obtained at Brown with comparable instruments at

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equivalent background brightnesses, while the naked-eye data did not agree well. The Dartmouth naked-eye ranges were considerably smaller than those observed at Brown, and it is possible that the two observers who provided these observations at Dartmouth had not developed the same skill in this slightly different observing situation that they had in their more extensive experience of observing with binoculars. At Brown, on the other hand, naked-eye observations received the same attention as the binocular observations and were obtained in parallel observing runs. Underestimation of the naked-eye ranges of course leads to overestimation of the "binocular gain," and this seems to be the best interpretation that can be found for the higher binocular gains recorded at Dartmouth. Whatever the explanation, the weight of experimental evidence favors the lower gains reported in the Brown studies.

Experimental Analysis of Unsteady Holding

Experiments were designed specifically to test the relative value of the threshold for naked-eye observation and for observation through binoculars. They showed a marked discrepancy between the two, in keeping with the findings at Brown.[2,3] Calculated at the retina, nearly 4 times as much light (total flux increment) was required at threshold when the target was viewed through a 10x70 instrument, hand-held, as was necessary with naked-eye observation. It was shown, moreover, that this discrepancy was the result of errors in holding the instrument in alignment with the eyes, combined with the effects of angular tremor that are unavoidable when the instrument is held in the hands. The experimental proof of this consisted in mounting the binoculars rigidly, and fixing the observer's head by means of a mouth-bite, so that his eyes were in correct alignment. Even with these precautions the movements of the eyes in scanning the binocular field caused misalignments that resulted in failure to utilize at all times the full brightness available. By requiring the observer to use a fixation mark and by providing artificial pupils in front of his eyes these errors were eliminated. Observations through the binoculars, compared with observations made with binoculars removed but with the observer and artificial pupils undisturbed, then yielded the same value for threshold (making proper allowance for the magnification and for the transmission of the instrument). This experiment proved that no factors had been overlooked that might affect seriously the detection of targets with the aid of binoculars.

Experiments next were performed to determine the relative contributions to lost efficiency by tremor and by alignment errors. A small spot of light was projected on a screen by means of a specially constructed, very light projector that could be clamped on the binocular itself without adding appreciably to its weight and balance. When thus mounted, the effects of tremor in holding the binocular were eliminated, and the image of the spot as seen by the observer appeared perfectly steady in the instrument's field. Thresholds obtained in this way were appreciably lower than when the same projector was mounted rigidly alongside the observer, so that the projected spot was stationary on the screen and, when viewed through the binocular, was subject to the usual unsteadiness. In both cases, of course, the usual alignment errors were effective, and the thresholds obtained with tremor eliminated were still not as low as was to be expected from naked-eye observation. Quantitatively, the results indicated that the losses were approximately equally divided between effects of tremor and effects of errors of alignment.

Both misalignment and angular tremor of hand-held binoculars were measured directly in special experiments, suggested by one of the members of Section 16.1. The alignment of the observer's eyes with the exit pupils of the binocular was recorded by infrared photography. Since the exit pupil and entrance pupil of an optical instrument are conjugate, a camera can be focused on the objective of the binocular to photograph the image of parts of the observer's eyes that are within the exit pupil. If the natural pupil is smaller than the instrument's exit pupil, or is not lined up with it, part of the observer's iris is photographed, imaged in the circle of the objective lens. The area included between the margin of the natural pupil and

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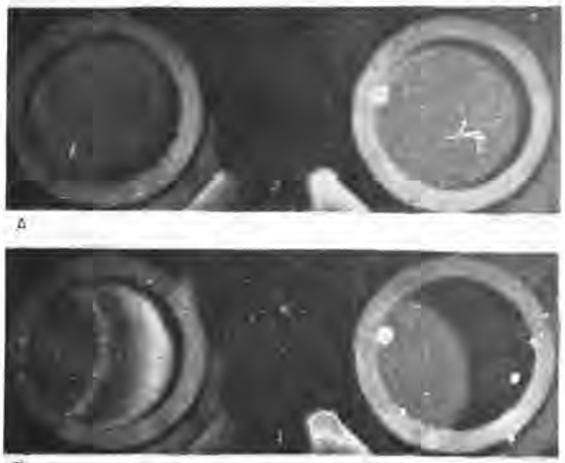
that of the exit pupil can be measured and the consequent brightness loss resulting from such "clipping" can be computed. Figure 5 is an example of the pictures thus obtained. The preliminary results indicate that unsteadiness of holding the instrument was not so much a source of clipping as were eye movements executed in scanning the binocular field. Special training and experience might make it possible for an observer to reduce losses from this source; a sufficiently large exit pupil would, of course, eliminate it.



A

B

FIGURE 5. Photographs by infrared illumination of the observer's eyes imaged in the objective apertures of a 9x63 binocular. The rims of the objective lenses are faintly outlined in white.

Upper photograph (A): binocular well aligned, observer looking at the center of the instrument's field; exit pupils fall almost entirely within the observer's pupils, only a narrow crescent of the edge of the iris (darker than the pupil) being visible inside the objective aperture. Lower photograph (B): binocular incorrectly aligned, the result of looking off to the side (observer's right) of the field; the exit pupils are "clipped" by the edges of the observer's irises, which are visible as crescents covering more than half of the instrument's aperture (darker than the pupil on the right side of the picture, brightly banded on the left). The right-hand objective (in the picture) was held slightly high in both photographs. (University of Pennsylvania studies.)

Direct measurement of angular unsteadiness was made from records of the actual tremor of hand-held binoculars. This was done in the laboratory and on a moving vessel (Navy binocular tests from a DE operating in Gardiner's Bay, off New London). For this a small, light camera ($f = 95$ mm) was attached to the binocular being tested, its film exposed for a second or more to a distant light that was being observed through the binocular. The irregular path traced by the image of the light on the film thus recorded the angular movements of the instrument during the exposure. The preliminary results obtained indicated that, in the laboratory, random tremor movements take place which in 1 sec cover an area approximately equal to a circle 1 mil ($3\frac{1}{2}$ min) in radius. On shipboard, even under the comparatively quiet conditions of the test, the tremor movements were two to three times as great as this. They were not greatly different with the largest instrument (10x70) than with the smallest (6x30). Wind (estimated 20 knots) increased them greatly; resting the elbows on a solid part of the vessel reduced them markedly, even in wind. Figure 6 gives examples of the traces photographed.

While these measurements of alignment errors and angular unsteadiness are interesting and valuable, the solution of the problem by such a direct approach promises to be long and difficult. The effects of brightness loss calculated from measured amounts of "clipping" can be translated fairly precisely into loss in range of visibility, for any given instant of time. However, as the eyes scan the binocular field and the "clipping" thus introduced varies from moment to moment, the net effect is not easy to assess. The effects of angular tremor are even more difficult to estimate. Discussions of these points are to be found at numerous places in the Brown final report,[2] as well as in the final report from Pennsylvania.[4]

ANALYSIS OF BROWN RESULTS

Because of the difficulties in making a direct analysis of the effects of unsteadiness of holding, the project at Pennsylvania devoted considerable attention to a less direct approach, based on the analysis of the data accumulated in the binocular tests at Brown. It was assumed that the failure to explain the binocular observations in terms of naked-eye data, after allowance for simple brightness losses, could be taken as a measure of the combined effects of misalignment and angular tremor, since these

were shown at Pennsylvania to be the only remaining factors. It was expected that the analysis would reveal certain consistencies that might permit useful generalizations to be drawn concerning the nature of these factors.

Thus it was expected that the series of experiments with binoculars of fixed magnification but varying exit pupil would reflect the fact that alignment is less critical if the exit pupil is either considerably larger or considerably smaller than the natural pupil. This it failed to do, and the reason for this failure is not understood.

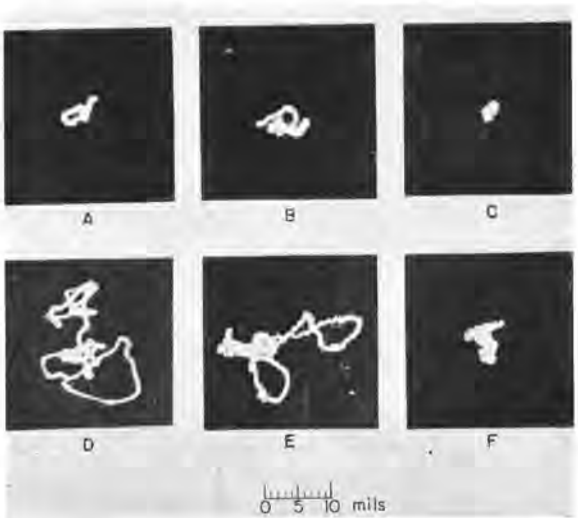


FIGURE 6. Records of the angular tremor of hand-held binoculars. Photographs of a distant light source taken with a camera mounted on a 10x50 binocular under various conditions of observing from the deck of a moving vessel.

Upper row (A-C), 1-sec exposures; lower row (D-F), 3-sec exposures. A, calm, elbows not rested. B, windy (estimated 20 knots), elbows not rested. C, windy, elbows rested on steady support. D, windy, elbows not rested. E, windy, elbows rested on vibrating support. F, windy, elbows rested on steady support. Scale of angular mils at bottom. (University of Pennsylvania studies.)

The analysis of the effects of tremor was more promising; moreover, the explanation of these effects required no new visual data. It has been pointed out that the visibility of a small target is determined by the product of its angular area and the brightness difference between it and its background. If the target is very small (less than 10^{-5} steradians), this threshold flux increment is approximately constant, irrespective of the size of the target. However, if the incremental flux from the target is spread over a large area of the retina, perfect spatial summation of the excitatory effects it produces no longer takes place, and a greater flux increment is required to render it visible. Naked-eye observations of large targets having low contrast provide the quantitative relation between target size and threshold flux increment at each level of background brightness. These data furnish a quantitative explanation for the diminished efficiency of binoculars of high magnification. The fundamental angular tremor of holding, magnified by the optical power of the instrument, in effect spreads the light in the image of the target over an area of the retina that is too large for complete spatial integration.

The application of these considerations to the analysis of the Brown data was made in the following way. The naked-eye data on targets of low contrast that were obtained in the course of the binocular tests provided the relation between target size and threshold flux increment at the four levels of background brightness that were used. Since the instruments introduced various amounts of brightness loss, it was necessary to devise a method for interpolating between the four observational brightness levels so as to construct curves relating target size to flux increment for any required brightness level, as computed at the retina. This interpolation was guided by an analysis of preliminary naked-eye data from the Tiffany Foundation project (Section 16.3, NDRC), although the data actually used were solely from the Brown observers. For any given binocular, therefore, it was possible to construct, for each brightness level used, the curve relating target size to flux increment that would be expected to describe the observations with that binocular if there were no effects of misalignment or tremor. The fact that the threshold value of flux increment of the target actually observed with the particular instrument did not fall on this curve at the actual value of target size (magnified image) was taken as evidence of the effects of unsteady holding. If it be assumed that angular tremor, magnified by the power of the instrument, in effect spreads the flux over an area larger than

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the actual target size, the size of this "effective area" may be computed from the curve. The mean angular radius of the area covered by the center of the target image in its erratic movements over the retina may thus be estimated for instruments of different magnification. The results are shown in Figure 7. The individual points show considerable scatter, indicating that the analysis is still not entirely satisfactory. Nevertheless, there is a distinct trend, showing increasing "effective area" with increasing magnification, in accordance with expectation.

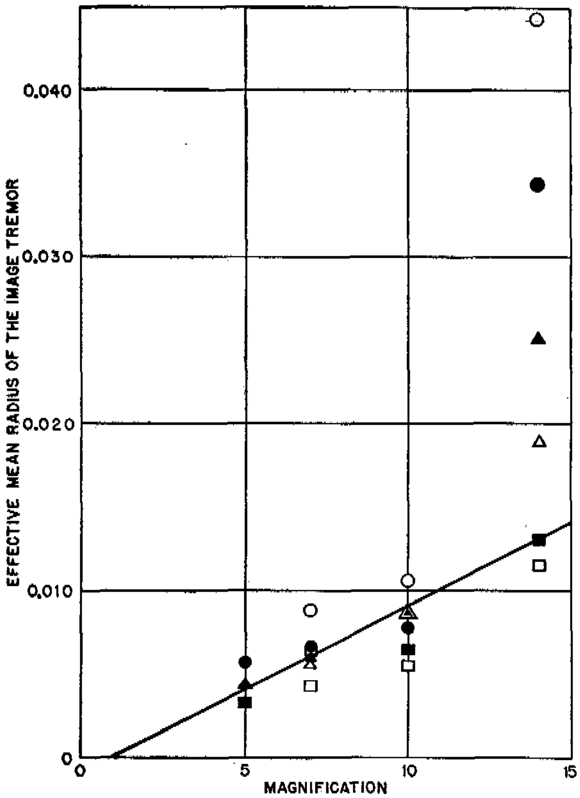

FIGURE 7. Calculated values of the amount of image tremor that must be assumed for hand-held binoculars of various magnifications to account for the difference between the naked-eye visibility of targets and the visibility of targets observed with binoculars, as determined at Brown University. Different symbols distinguish the values obtained for different levels of background brightness and target contrast: circles, 40 mμL background brightness; triangles, 400 mμL; squares, 4000 mμL; solid circles and triangles, contrast = 1.0; solid squares, contrast = 0.6; hollow figures, contrast = 0.4. (University of Pennsylvania studies.)

The ordinates in Figure 7 give the values of the angular radius, in radians, of the circular area that is assumed in effect to be covered by the center of the target image in its random movements resulting from angular tremor movements of the binocular, magnified in the field of the instrument. The line drawn exhibits a proportionality between mean "tremor radius" and M-1 (angular movements of an instrument of unit power produce no apparent image displacements). The slope of this line indicates a "basic tremor radius" of 1 mil, which is in agreement with the measured estimate of the area covered in 1 sec by tremors of hand-held instruments indoors. Of course, 1 sec is too long an interval for temporal summation in the retina, for the retinal "action time" is of the order of $\frac{1}{5}$ to $\frac{1}{2}$ sec at these brightness levels. However, the analysis as presented so far takes no account of the effects of misalignment. If allowance is made for brightness loss from this source, smaller values for the "basic tremor" are obtained in better agreement with known properties of the retina.

The observations with the $14\times$ binoculars were thought (Brown University report)[2] to be unfavorable to this magnification because of poor eye relief and small field of the instruments. This would tend to make the calculated tremor radius too high at this magnification.

Thus while the attempts of the Pennsylvania project to analyze the data provided by the binocular testing projects were only partially successful, they offer considerable promise. Further experiments are needed, and more knowledge must be obtained of the fundamental physiological processes of spatial and temporal summation in the retina and other parts of the visual nervous mechanism. It is reasonable to hope that it will be possible ultimately to predict the aid to vision that may be expected from various optical instruments under various conditions of observation.

ADDITIONAL PROJECTS

Eye Guards. Two projects of immediate practical interest were undertaken at Pennsylvania. The construction of "eye guards" for attachment to standard binoculars was undertaken, in the hope of improving the ease and comfort

of use, and perhaps of reducing alignment errors. Tested briefly at Brown University, no significant improvement in target visibility resulted, in the quiet conditions of the laboratory. However, binoculars equipped with these eye guards are considerably more comfortable to use, and these or similar devices would probably have important practical advantages. An experimental prototype of the eye guard developed at Pennsylvania was sent to the Naval Gun Factory for further engineering prior to Navy tests.

Folded Binoculars. The design and construction of a "folded" binocular (10x70) of unconventional type was undertaken at Pennsylvania. This was done as an experiment to determine whether improvement in weight distribution would decrease angular unsteadiness, especially during long periods of fatiguing use. In this instrument the four reflections of the Porro erecting system were redistributed along the optical axis. The objectives were brought to either side of the head, and the center of gravity was back of the eye position. The altered distribution of the bulk in this design might make it useful in cramped quarters, as in airplane enclosures. It could conceivably be mounted on the observer's head, to be swung down into place when needed and steadied by one hand. Tested at Brown University under quiet conditions indoors, this binocular yielded slightly poorer results than the conventional 10x70. The possibility of lessened fatigue over long periods of use has not been explored. This line of development has greatest interest in making available for hand-held use, or for use in cramped quarters, instruments that are much larger than could otherwise be considered.

5.5 DISCUSSION

The laboratory studies that have been described have demonstrated clearly that binoculars aid considerably in the visual detection of objects under conditions of low illumination similar to those found out of doors at night. This is in agreement with much practical experience and with expectations based on elementary considerations. This conclusion refers to the use of hand-held binoculars under the favorable conditions of the laboratory, in the absence of wind, vibrations, atmospheric effects, etc. The conditions of the experiments were confined to comparatively simple problems of observation, where the discrimination of significant objects from irrelevant details of the visual scene were not required, and where different kinds of objects did not need to be recognized and distinguished. Problems of search were not included, observations being limited to the detection, with a specified probability, of objects in one of a few possible known locations. The study of the utility of binoculars must ultimately be extended to include these and other conditions that are of importance in practical seeing. The results of the present study, nevertheless, will prove useful in guiding decisions concerning the design of night binoculars and their use in practice.

The assistance to vision that may be expected from the use of any hand-held binoculars at night, according to the fairest appraisal of the laboratory studies that seems possible, is at most a 4½-times increase in the range at which objects can be detected as compared with naked-eye observation. This is the maximum binocular gain reported in the Brown University study[2] at the higher background brightness levels corresponding to a starlit sky or brighter. At lower brightness levels the gain was less (3 times naked-eye range). Binoculars that are of assistance on the brighter nights may be less useful under very dark conditions.

The Brown University project demonstrated clearly that there was an optimum magnification for hand-held night binoculars of given objective diameter. For both the 50-mm and 70-mm sizes, this was at 10× at all brightness levels studied except the lowest (corresponding to very dark conditions). Under the favorable observing conditions of the laboratory, it paid to increase the magnification up to 10×, but further increase resulted in a distinct decrease in performance. This falling off was so marked that it seems unlikely that the optimum magnification for any hand-held instrument is above 10×.

All conditions of practical seeing such as wind, vibration and motion of the observing

platform, and necessity for scanning, will tend to favor the use of lower rather than higher magnifications for hand-held instruments of general utility, so that a magnification lower than 10× may prove to be a more acceptable practical compromise.

The series of experiments on the effects of exit pupil size indicate that night binoculars should have an aperture large enough to take advantage of the light gathering power of the dark-adapted eye, with its expanded pupil. Notable increase in the range of detection with increasing exit pupil has been demonstrated up to a diameter of 6 mm; above this the returns are meager. It is not clear why this should be, since the average pupil diameter for observers adapted to night sky brightness levels is approximately 7 mm, and it might also be expected that still larger exit pupils would allow a margin for minor misalignments and so reduce the chance of brightness loss from this cause. Until these experimental results have been verified, or a plausible explanation for them has been found, sacrifice of exit pupil size below 7 mm should be made reluctantly.

Sacrifice of exit pupil may be justified in some cases. An example is the 10x50 (wide field) binocular, which may be compared with the standard 7x50 of similar size and weight. In this case the exchange of exit pupil size for extra magnification was profitable, at least for the laboratory conditions of observation. The 10x50 yielded ranges that were approximately 7 per cent higher than could be obtained with the 7x50 under comparable conditions, at the higher levels of background brightness. A further increase, of about the same amount, was obtained by increasing the objective diameter of the 10× instrument to 70 mm, thus regaining the 7-mm exit pupil, but since this entails considerable increase in bulk and weight, it is doubtful whether it would be warranted for a hand-held instrument of conventional design.

The increase in the range at which objects can be seen at night with the aid of hand-held binoculars of the most favorable design is great enough to be of considerable advantage in practice. Nevertheless, it is disappointingly small compared to what might reasonably be expected. This verdict is based largely upon the results of the Brown University studies.[2,3] Experiments at the University of Pennsylvania confirm it, and it is in agreement with the results of a similar study by British workers. The Dartmouth results contradict this verdict, but the best appraisal that can be made at present favors the interpretation that the Dartmouth naked-eye ranges must have been in error. They appear to be too low, and the binocular gains calculated from them consequently appear to be too high. Whatever the explanation of the Dartmouth results, the conclusions drawn from them concerning binocular gain cannot be accepted. It seems quite certain that hand-held binoculars do not provide the full increase in range of vision that would be expected from their magnification, after allowance for simple brightness losses alone.

The attempts to come to a complete understanding of the factors affecting visual performance with binoculars have been only partially successful. The experiments at Pennsylvania showed that strict experimental control of alignment and steadiness resulted in complete agreement between naked-eye thresholds and thresholds obtained with the aid of binoculars, after allowance for magnification and simple brightness losses. There appear to be no unexplained factors remaining. Although the experiments were performed with bright targets against a completely dark background, it seems likely that similar results would be obtained under conditions more closely resembling the practical situation at night. The fields of the binoculars in question are so large that the slight restriction they place on the normal naked-eye field can hardly be an important factor where search is not required.

The experiments at the University of Pennsylvania demonstrated that the reduced efficiency of hand-held binoculars, after allowance for simple brightness losses, is caused by failure to keep the instrument in alignment with the eyes, especially when scanning its field, and by angular tremor movements from unsteady holding which cause the image to "dance" about in an irregular manner. The losses appear to be about equally divided between the effects of these two factors, each accounting for the loss of roughly 0.15 log units of range.

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The direct measurements of misalignment and of angular tremor are valuable chiefly in confirming the presence of these two factors and in giving an approximate indication of their magnitude. The application of such measurements to a detailed analysis of visibility losses promises to be difficult and presupposes a greater knowledge of visual physiology than exists at present. Less rigorous application, however, is very instructive. Thus the fact that misalignment is caused largely by movements of the eyes themselves, rather than by unsteadiness of holding the binocular, indicates that mounting the instruments or providing them with eye guards to locate them accurately in front of the eyes will not eliminate this source of trouble entirely, valuable as such devices may be. Training the observer, on the other hand, may be quite effective in reducing losses from misalignment. The observer should learn to move the binoculars rather than his eyes, and since peripheral vision must be employed, he must learn to give his attention systematically to various portions of the field without changing his direction of fixation down the axis of the instrument.

The measurements of angular tremor are also useful in a qualitative way. From them it was learned that differences in size and weight of the instruments tested had little to do with the steadiness with which they could be held, but that external conditions of vibration and wind were very important. Arrangements for sheltering the observer from wind and provision for vibration-free rests for his elbows are practical aids that would yield large returns in visual performance.

The attempts to analyze the results of the binocular studies on the basis of naked-eye thresholds have been promising but not entirely successful as yet. The Dartmouth results as originally analyzed proved to be misleading in the light of later surveys; the conclusion that magnification alone, after correction for simple brightness losses, is sufficient to account for binocular performance is almost certainly wrong. The results from Brown University, where naked-eye observations were routinely obtained along with the observations with binoculars, are more reliable in estimating the binocular gains that may be expected and in permitting analysis of the effects of tremor and misalignment. Even here there are puzzling questions. If misalignment contributes notably to binocular losses, why does not the range of visibility increase steadily with increasing exit pupil, even above the value for the average diameter of the observer's natural pupil? With an oversize exit pupil a certain amount of misalignment could presumably be tolerated without causing brightness losses from clipping. Furthermore, exit pupils that are smaller than the natural pupil should also permit some degree of misalignment before the effects of clipping become evident. Since all apparent brightnesses are calculated from the smallest limiting aperture, whatever additional losses arise from misalignment should be least noticeable if the exit pupil is either much larger or much smaller than the natural pupil. Failure of the observed range of visibility to agree with the "expected" range should be most noticeable when the two apertures are exactly the same size. Then the slightest misalignment will result in "unexpected" brightness loss. Analysis of the "exit pupil series" of experiments at Brown showed no evidence of this effect of misalignment. The reason for this is not clear, unless it be that the effect was masked by the considerable variation in pupil size in the normal population of observers.

The analysis of the effects of angular tremor of the hand-held instruments was more successful. Based on the assumption that rapid, erratic tremor movements cause the target image in effect to be "smeared out" over an angular area greater than its actual size, the binocular losses could be explained fairly satisfactorily by reference to naked-eye data, giving the increase in threshold attendant upon decreasing the contrast in proportion to the increased size of the spread-out image. The higher the magnification, the greater is the area over which the target image must be assumed to be spread in order to account for its diminished visibility, in keeping with the idea of a "basic angular tremor," the effects of which are magnified by the optical power of the instrument. The Brown data support this interpretation with moderate consistency, except

for the case of the 14× instrument, for which the losses are exaggerated. There is a good excuse for this, since the 14× instruments were not carefully designed instruments and had limited field. The observers found it necessary to modify their observing technique with these instruments and this could easily account in part for their poorer performance.

The value of the "basic angular tremor" that must be assumed in order to explain the Brown data agrees satisfactorily with that obtained by direct measurements under laboratory conditions, making proper allowance for known properties of the retina. In regard to the effects of angular unsteadiness, therefore, a consistent interpretation has been found. While this interpretation cannot be said to have been proved rigorously, it is the best available at present and it offers promise of considerable utility. If it can be extended on a sound basis, it may be ultimately possible to predict with moderate accuracy the aid to vision that binoculars of various designs will furnish under various conditions. Not only is it useful to know what may be expected in practice, but such prediction would be valuable in determining the optimum design features of binoculars for various purposes.

The experimental binoculars of unconventional design (folded optical path) that were designed and constructed at the University of Pennsylvania proved disappointing in laboratory tests. In the light of the subsequent finding that weight and balance of an instrument have little effect on angular tremor, this can be understood. It is still possible that such an instrument may be useful in special applications, or that it may be less fatiguing to use over long periods of time, but it seems clear that no very marked improvement in performance can be expected in this direction. It does offer the possibility of using considerably larger instruments than would be possible with conventional designs.

The eye guards designed at Pennsylvania likewise yielded no very tangible improvement in binocular performance when tested at Brown, although the observers commented favorably upon them. It is almost certain, however, that in this case the increased comfort and lessened fatigue that this device is certain to provide warrant the adoption of this accessory or its equivalent.

It was stated in the final report from Brown University[2] that no single improvement of binocular design taken alone contributed very notably to increased range of detection of targets. Large exit pupils gave disappointingly small improvements. Even the higher magnifications were not as valuable as might reasonably be expected, and if too high were detrimental to performance. Binoculars mounted on alidades, which presumably eliminated most of the angular tremor, failed to give the full advantage that was expected. The improvement in comfort obtained by the use of eye guards failed to give tangible returns to better performance. To this may be added the finding of the British report[16] that even the practice of coating the optics with low-reflection films was found to yield only a slight improvement in visibility through the instruments. It might well be questioned, in each instance, whether the slight gains obtained were worth the trouble and expense. Such a conclusion, however, would be a serious error. The very fact that there are many minor details all making slight contributions to the net efficiency makes it all the more necessary to pay strict attention to every feature of design and manner of use that might possibly contribute to improved visual performance with binoculars. In addition to the features that have been discussed, this includes the practice of careful focusing of the instruments, careful adjustment of the interpupillary distance, and attention to other rules of use that are easily overlooked. Above all, it calls for careful training of the observers in the use of their eyes at night and in the special skills connected with the use of binoculars to aid their vision.

5.6 RECOMMENDATIONS BY NDRC

1. A program of laboratory studies should be continued, aimed at a complete understanding of the various factors which are involved when optical aids are used to increase the range

of detection for targets at night. These studies should include:

a. Experiments planned to explain the unexpectedly small increase in range which results from increasing the exit pupil diameter above 6 mm and the failure to find a reduction in the "expected range" for binoculars when the exit pupil nearly matches the pupil of the eye. Explanation of this phenomenon will undoubtedly throw important light on the whole situation relating to the night use of binoculars.

b. Studies of the effect of increasing the angular field of view, both with "dummy" unity-power binoculars and with ordinary 7x50 binoculars, on ability to detect targets in unknown locations. This study should be made for targets whose location is unknown both in one and in two coordinates (corresponding to horizon and sky scanning). Special laboratory equipment will be required, perhaps based on the use of large mirrors mounted on axes of rotation. Tests on ships should also be made.

c. Measurements of clipping and of angular tremor should be made on a number of different observers and on several standard binoculars.

d. The effect of adding extra weight on arms attached to binoculars, in order to increase moment of inertia, with provision for relieving the observer from carrying this weight, should be investigated. The effect on angular tremor and on range of detection should be studied.

2. A program of tests on shipboard should be carried out, with carefully planned targets, to establish the scoring of relative range with different instruments on a quantitative basis. Consideration should be given to using a series of targets of different sizes, all at the same distance, to eliminate the differential effect of haze. It would be extremely desirable to conduct these tests in a region where the air is highly transparent at night, perhaps in the tropics. Such a location would greatly increase the consistency of the results and would make it possible to establish data on a reliable basis in a much shorter time than if the work were done under variable conditions of visibility. The program should include the following:

a. Studies of the effect of increasing the angular field of view, both with "dummy" unity-power binoculars and with standard 7x50 binoculars, on ability to detect targets in unknown locations, both along the horizon and in the sky. This program should be closely related to the corresponding program in the laboratory. The field can be controlled by adding diaphragms to wide-field binoculars.

b. The effect of eye guards on binoculars should be determined under various conditions, including wind, cold, vibration, roll, and pitch. It is likely that eye guards will prove to be more advantageous on shipboard than in the laboratory.

c. The optimum combination of magnification and exit pupil (when the aperture is fixed) should be determined under various conditions, including wind, vibration, roll, and pitch. It is likely that the optimum combination will be appreciably different on shipboard from the result (10x50) established in the laboratory.

d. The effect of fatigue on the best compromise between magnification and exit pupil should be investigated by comparing limiting range at various intervals after the lookout has started to observe. This test will also give important information for use in establishing lookout schedules.

e. The effect of adding weighted arms to binoculars to increase the moment of inertia should be tested on shipboard, with provision for relieving the observer of the added weight by means of a coiled spring above or below the binocular.

f. An overall test should be made to determine the increase in efficiency of a lookout that results when every provision,

[redacted]

which individual tests have shown to be effective, has been made for increasing his performance. The test should probably include the use of 10x50 binoculars, eye guards, weighted arms attached to the binoculars, vibration-absorbing elbow rests, and a shelter from the wind closed on three sides, with an opening in the front just large enough to cover the assigned sector with a reasonable margin.

3. Lookouts should be trained in the best use of binoculars, on the basis of the findings which result from the laboratory and shipboard tests. Particular attention should be given to directing the eye along the axis of the instrument, while the attention is directed peripherally, if this is found to be the best procedure.

4. The extent to which emphasis should be put on the further development of wide-field binoculars should be determined as a result of tests made in the laboratory and on shipboard with instruments having fields of various diameters.

Chapter 6

HARMONIZATION OF B-29 GUNS AND SIGHTS

By *Theodore Dunham, Jr.*[a]

In the B-29 aircraft the guns are located at considerable distances from the sights and are operated by servo control. When the computer is not operating, the aim in directions of guns and sights must be held accurately parallel to one another at all settings of azimuth and elevation. This requires that the azimuth axes of guns and sights be parallel and also that the elevation axes be perpendicular to their respective azimuth axes.

At the modification centers, harmonization was carried out by using plane mirrors set up parallel to one another opposite each station, so that the guns and sights could be lined up optically without difficulty and with little expenditure of time. Aircraft ordinarily left the United States with the guns and sights harmonized, but the adjustment was often seriously disturbed later as a result of combat activities and rough landings. Moreover, it was frequently necessary to replace turrets and sights which required harmonization before they could be used. Accordingly, there was urgent need for a method of harmonization which could be used in the field.

The *middle distance yard method* is usually employed for field harmonization. This method is quite satisfactory from the point of view of speed and accuracy, but requires an open area extending at least 500 ft from the bomber in four directions. In the Marianas, where the need for harmonizing aircraft was acute, it was not possible to provide sufficient space for this method. The aircraft were located on narrow hardstands close to one another for servicing between raids and there were often sharp declivities on both sides. Under these conditions middle distance yards could not be employed. Several such yards were established in the Marianas at special locations, but it was impractical to tow the aircraft from their hardstands to these locations solely for the purpose of harmonization, since to do so would seriously interrupt servicing activities and would increase unduly the inactive period between raids.

[a] Chief, Section 16.1, NDRC.

In view of this situation, the Army Air Forces requested NDRC to develop a field method of harmonization which could be employed in a limited space with portable equipment. The project was assigned to the Applied Mathematics Panel [AMP] late in 1944, as part of Project AC-92, which covered the general B-29 fire-control problem. Section 16.1 cooperated with AMP in devising plans and providing facilities for this program. However, it soon became clear that the problem involved primarily the development and testing of special optical equipment. Accordingly, Project AC-127 was established and assigned to Section 16.1 in March 1945.

The following were agreed upon by all concerned as satisfactory requirements for a field method of harmonization:

1. Overall accuracy should be at least 2 mils, preferably 1 mil.
2. The equipment should be simple enough to be operated by regular armorers with limited additional training.
3. The device should make it possible to harmonize an airplane standing at dispersal points without necessarily placing it on jacks.
4. Space requirements around the fuselage should not exceed what is available at stations in the Marianas. This is extremely limited, since the terrain frequently pitches off steeply at the very edge of the hardstands. At the most, not over 100 ft from the aircraft should be required for operation.
5. The time required for harmonization should not be unduly long, preferably not more than 3 or 4 hours.
6. The equipment should be suitable for use by day or by night.
7. The equipment should not be unduly heavy, bulky, or expensive, and should not be unreasonably difficult to produce.

The importance of the problem appeared to justify parallel efforts by more than one group, followed by comparative field tests of all promising prototype equipment at the earliest possible date. The University of Rochester[1] and the Massachusetts Institute of Technology [MIT][2] undertook the development of the *prism method* and the *wire method*, respectively. Merrill Flood and Associates [MFA] developed the *mirror boresight method*[3] for harmonizing certain combinations of guns and sights and developed an overall procedure (the MFA method)[4] for harmonization which employs both the wire method and the mirror boresight method, each for those combinations for which it is best adapted. MFA also cooperated in the final testing and evaluation of the various methods. Harvard University developed the *mirror frame method*.[5]

6.1 THE PRISM METHOD

6.1.1 Principle of the Method

The prism method provides means for establishing two portable targets, much closer than the middle distance yard targets, so located that when the gun and sight are aimed at these targets they will be parallel. The targets are set up separately for each of the ten gun and sight combinations which must be harmonized. The settings of selsyns and the electrical adjustments are made according to the directions given in the Technical Order [TO][6] for middle distance yard harmonization.

The method is based on the principle of locating optically two lines, in a plane containing both the gun and the sight, which are parallel to one another, by making equal the two angles formed by the intersection of these lines with a third line. Two identical 6-degree double-image prisms are used to set these two angles equal. Figure 1 shows the arrangement of the various elements for harmonizing a gun and sight.

6.1.2 Equipment

The *field prism* is a double-image prism consisting of two pieces of glass cemented together with a partially reflecting, partially transmitting interface. The prism transmits one beam undeviated and offsets the other by 6 degrees. This angle is accurately established by the control of the fine grinding and polishing of the

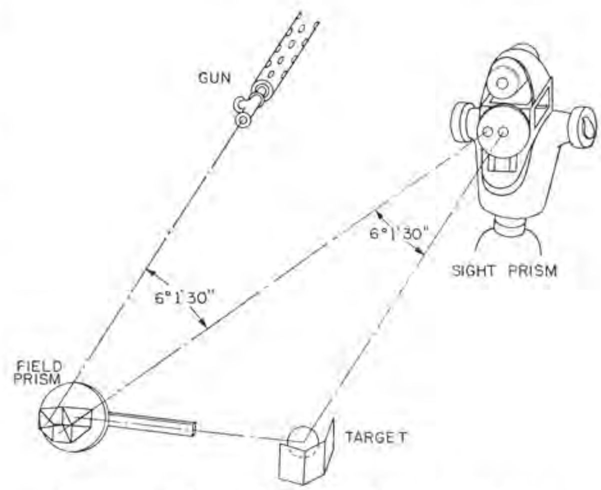

FIGURE 1. Optical layout of prism method.

parts of the prism, and is later verified after cementing. The prism is mounted in a swivel head on an M-5 Army tripod (see Figure 2) with provision for rotating it around the undeviated beam. A cross-sight slit and wire are

FIGURE 2. Field prisms.

mounted on the front face of the prism unit, aiming across the line of sight in the plane defined by the deviated and undeviated beams. A cross-sight arm is attached at one side to aid the operator at the sight prism in estimating

the plane defined by the two beams. A 2.5X Galilean telescope may be attached to the prism unit when desired to facilitate settings and to increase accuracy.

FIGURE 3. Sight prism and adapter for pedestal sight.

The *sight prism* and its mount are identical with the field prism. An adapter (see Figure 3) is provided to fit the front of the pedestal sight.

FIGURE 5. Sight prism and adapter for ringsight.

Figure 4 shows the sight prism on the pedestal sight with the Galilean telescope in place. A different adapter is used for the ringsight (Figures 5 and 6). The sight prism has no cross sight.

The *field target* is a white ball 1½ in. in diameter, partially surrounded by a black shield,

FIGURE 4. Sight prism and adapter installed on pedestal sight.

and mounted on a brass tube which slides through the top of an M-5 tripod to permit adjustment in height. Four 24-in. sections of tubing are provided, so that this target can be located up to 8 ft above the tripod head.

FIGURE 6. Sight prism and adapter installed on ringsight.

A *gun target* and *boresight telescope* are attached to the gun which is to be harmonized. The gun target is a 6-in. white disk which slips over the end of the gun barrel. A standard boresighting telescope is set in the muzzle and is used to sight the gun at the field prism.

6.1.3 Procedure

A crew of four men should be available, if possible, so that all stations can be manned simultaneously. Three men can do the work, however, since the target can be adjusted by the field prism operator if necessary.

The double-image field prism is located on its tripod at such a distance from and at such orientation to the aircraft that the gun and sight are seen superposed. This means that the gun and sight subtend an angle of 6 degrees

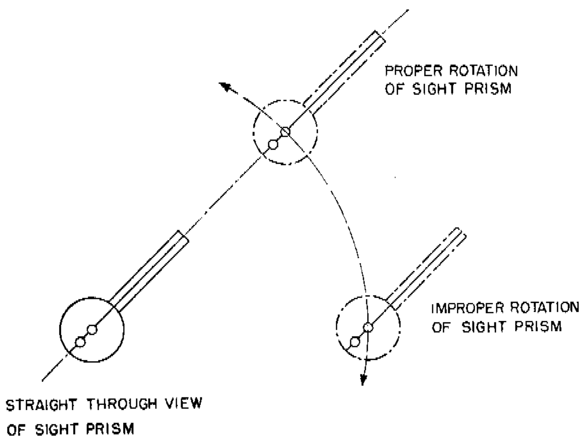

FIGURE 7. Setting rotation of sight prism so that images of cross-sight arm on field prism are in line.

as seen from the field prism. The gun is aimed at the field prism. The sight prism is placed on the sight, and the latter is aimed, using the deviated beam of the sight prism, at the field prism. The sight prism is rotated until the plane defined by its two beams agrees as closely as possible with the plane defined by the two beams of the field prism. The correct orientation is judged by making the deviated image of the cross-sight arm on the field prism line up with the direct image of the cross-sight arm, as in Figure 7. The target is used to make this setting more accurately. It is located at a distance from the field prism approximately equal to the distance of the gun from the sight, on the side of the sight, and is placed as nearly as possible along the line of the cross-sight arm. The field prism operator then directs the target operator to place the target more exactly in the cross-sight plane by sighting through the cross sight. The sight prism operator verifies whether the undeviated image of the target lies somewhere on the cross-sight arm. If it does not, the sight prism operator rotates his prism until the cross-sight arm on the field prism appears to aim directly at the target. He then aims the deviated reticle dot directly at the center aperture of the field prism, using the Galilean telescope as a check. If the target does not lie somewhere on the cross-sight arm, he directs the target to move until it is perpendicular to some part of the arm, after which the field prism operator directs the target to move back into the cross-sight plane (see Figure 8). This should place the direct image of the target somewhere within the length of the deviated image of the cross-sight arm, as seen by the sight prism operator. If so, he makes a final setting of the rotation of the sight prism to bring the target to the mid-line of the cross-sight arm. When this is done, and the reticle dot is still aimed at the central opening of the field prism, the gun and sight are parallel, just as they would be if they were sighted on middle distance yard targets. Selsyn signals can be

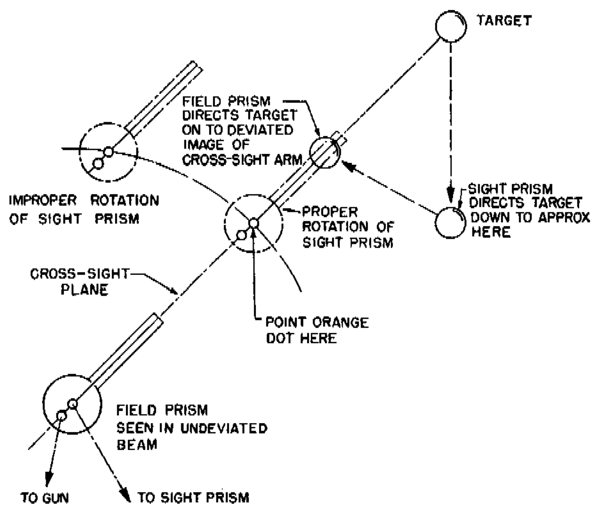

FIGURE 8. Setting undeviated image of target on deviated image of cross-sight arm.

read and electrical adjustments made in accordance with directions in the TO.[6]

The above description is an abbreviated version of the full directions for setting up the two double-image prisms, the target, and the gun. Full instructions for carrying out the various

[redacted]

steps in a logical sequence are given in the University of Rochester report.[1a] The procedure is actually much simpler than it appears to be from the written instructions. With flashlights it can be carried out almost as easily at night as by day.

The recommended positions for the field prism for each gun to sight combination is shown in Table 1. The approximate locations of the field prism and target for each of these combinations are shown in the sketches in Figures 9 to 16.

TABLE 1. Recommended positioning of field prism for each sight to gun combination.

Turret and sight	Height of field prism above ground (feet)	Angle at sighting station from field prism to nose of ship (degrees)	Distance from sighting station to field prism (feet)	Height of target above ground (feet)
LAT—RS* (Figure 9)	4	120	170	7
RS—LFT* (Figure 10)	3	45	300	
LFT—NS (Figure 11)	2	45 to left of nose	100	8
ALTERNATE	2	100 to left of nose	160	8
NS—UFT† (Figure 12)	10	45 to left of nose	100	7
ALTERNATE	6	100 to left of nose	160	3
UFT—RING S‡ (Figure 13)	6	150 to left or right of nose	250	5 (or about 1 ft below field prism)
RING S—UAT§ (Figure 14)	About 4½ ft above cabin of plane	0	10	No target used in this position
LS—LAT Same as LAT—RS				
LS—TM (Figure 15)	5	160 to left of nose	125	3
RS—TM	5	160 to right of nose	125	3
TM—TS (Figure 16)	4⅔	180 from nose (straight back from tail)	30	7½

* A 12° prism would greatly reduce distance from field prism to sighting station.
† Field prism should be as high as possible.
‡ In this position the field prism should be located as high as possible in order to view through good Plexiglas in right sight. Positions more toward the tail of the plane may be used, but they require a stand for the guns to be above the follower.
§ This position is reached by standing on top of the cabin in front of ringsight.

The carrying case containing all of the equipment, except the two tripods, required for the prism method is shown in Figure 17. The total weight of the equipment, including tripods, is about 30 lb.

The tripods can be placed on the ground for all gun to sight combinations except the ringsight and upper aft turret, for which the field prism is mounted on top of the aircraft. It is necessary that the ground should not fall off much below the level of the aircraft for a distance of about 200 ft in the forward and sideways directions. A distance of 250 ft, without much drop below level, is required 30 degrees on one side of the tail, but only 30 ft is required directly behind the tail. If a 12-degree prism were used instead of a 6-degree prism, the distances would be reduced by one-half, but difficulties would be encountered in fitting a prism with the wider angle to the sight.

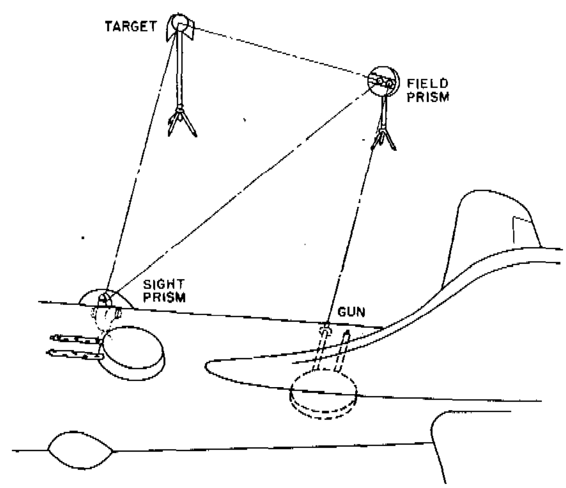

FIGURE 9. Lower aft turret to right blister sight.

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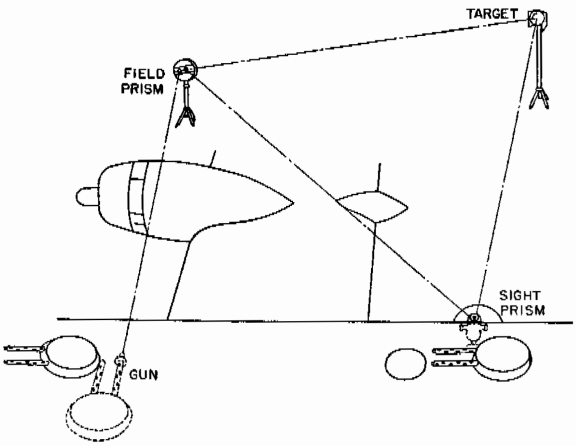

FIGURE 10. Right blister sight to lower forward turret.

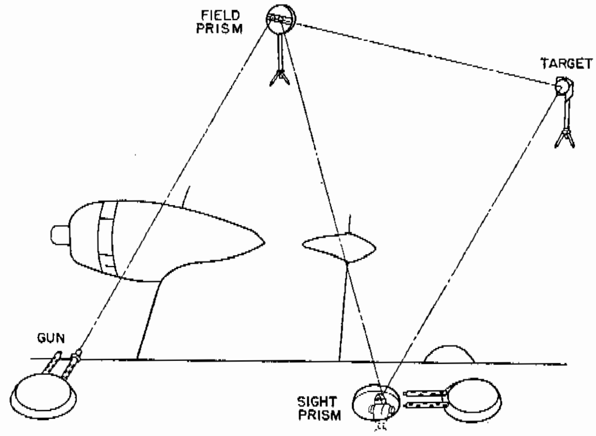

FIGURE 13. Upper forward turret to ringsight.

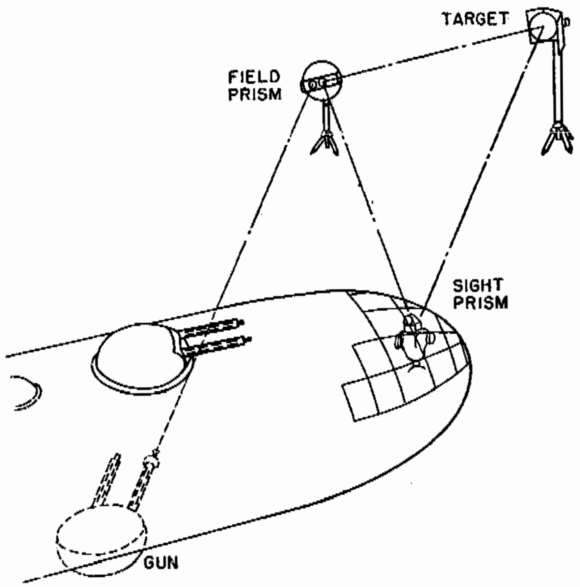

FIGURE 11. Lower forward turret to nosesight.

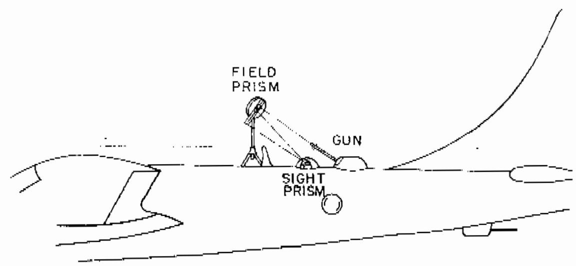

FIGURE 14. Ringsight to upper aft turret.

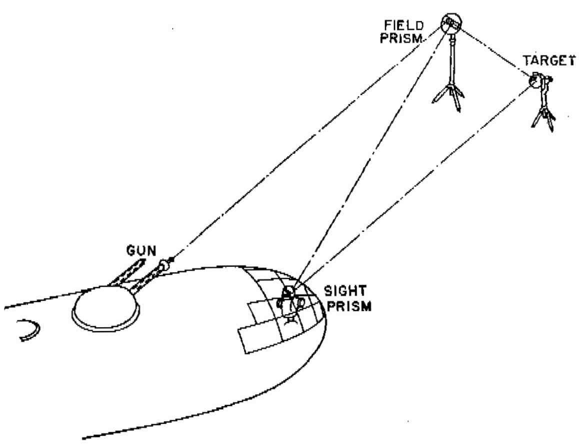

FIGURE 12. Nosesight to upper forward turret.

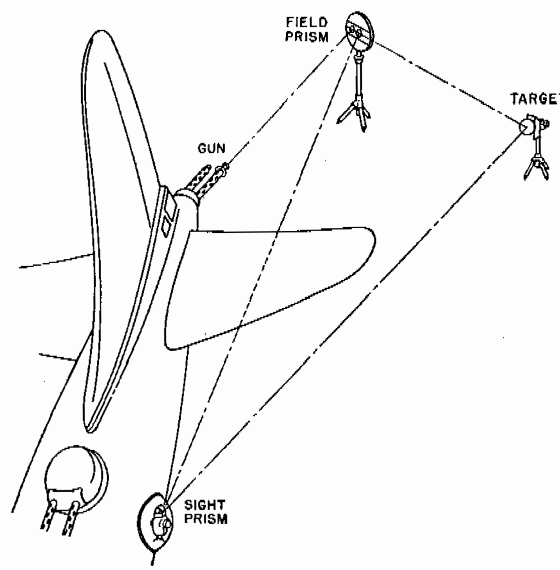

FIGURE 15. Left blister sight to tail mount.

6.1.4 Tests of the Prism Method

Tests were carried out at Bedford, Mass. in August 1945 on B-29 aircraft. Enlisted men, most of whom were instructors in gunnery at Laredo, were instructed in this method as well

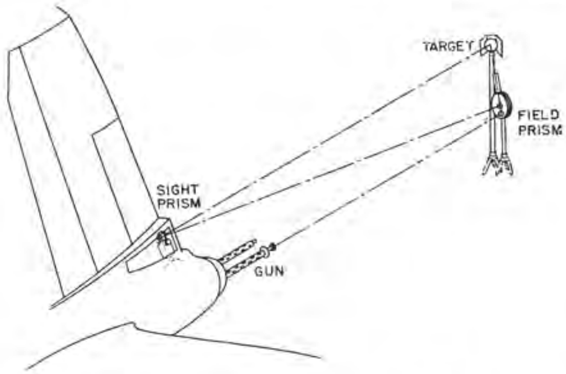

FIGURE 16. Tail mount to tailsight.

as in the wire method. After two weeks of experience with both methods, they were able to harmonize all stations, using the prism method, in slightly more than 3 hours, including the setting of selsyns. The time required for set-

FIGURE 17. Case with equipment for prism method.

ting up the targets at one pair of stations averaged about 5 min. When successive target setups were made, the indicated errors in harmonization showed a mean deviation of about 1 mil. Individual settings of the gun and sight on the targets in any one setup showed mean deviations of less than half a mil.

6.1.5 Discussion

The prism method is entirely practical. It provides the necessary accuracy and the time required is entirely satisfactory. The equipment more than meets requirements on weight and compactness. The only obvious drawback to the method is the extent of relatively level ground which is required around the aircraft.

Three sets of equipment for the prism method were made up in July 1945, and were shipped by air to the Marianas in August with the twelve men who had been trained in its use.

6.2 THE WIRE METHOD, MARKS I AND II

6.2.1 Principle of the Method

The wire method is based on establishing two lines parallel to each other by relating them in azimuth to different parts of a wire under tension and in elevation to a level bubble (see Figure 18). By using this principle it is possible to set two telescopes parallel, one in front of a sight and one in front of a gun. The first allows the observer to see the central dot of the reticle reflected in a triple mirror, and to signal to an assistant who can move the sight until the dot falls on the cross wires of a reticle in the telescope. The second instrument looks into a mirror mounted perpendicular to a bore pin in the muzzle of the gun, and allows the observer to direct an assistant to set the gun so that the image of a central bead on the objective falls on the reticle of the telescope. Under these conditions the gun and sight are parallel, and electrical adjustments can be carried out in accordance with the procedure outlined in the TO for middle distance yard harmonization.

6.2.2 Equipment

Preliminary experimental equipment which was used for tests at Bedford, Mass. in April

1945 is referred to in reports as the Mark I equipment. Improved equipment was tested at Bedford in August 1945 and is referred to as Mark II equipment.[2] The improvements consisted principally in increasing the stiffness of supporting members and increasing the ease of operation, but did not involve any change in general principles of design. Accordingly, the following brief description is based on the Mark II equipment.

A piano wire, 0.020 in. in diameter, and up to 60 ft in length, is used to define the azimuth of the gun and sight. It is stretched just above the level of the ground by means of a cylindrical spring which maintains a tension of about 40 lb. The ends are attached to aluminum platforms with three pointed legs, weighted with sandbags so that they will hold on a hardstand (see Figure 19).

One-half of a standard 6x30 (Ordnance M13A1) binocular is used for the sighting telescope, while the other half is used to make the setting perpendicular to the wire (see Figure 20). This azimuth-level instrument is equipped with a level bubble. A double-image prism (see Figure 21) in front of the right-hand objective brings into the field of view two sections of the wire, approximately 7 degrees to the right and left of vertical. A 14-degree prism is used, with a 28-degree prism cemented to its middle third. Auxiliary lenses are moved into position in front of the objective to make it possible to focus on the wire. Cross wires are installed in the focal plane of the left-hand telescope, and a bead is mounted at the center of its objective. A battery and miniature lamp is provided for illuminating the bead at night. The instrument is mounted on a standard surveyor's leveling head provided with an azimuth clamp and slow motion tangent screw. A pair of identical instruments is adjusted so that the lines of sight of each have the same azimuth and elevation when set on the same wire and leveled.

It is necessary to provide means for locating one instrument in front of the gun and one in front of the sight, with an accuracy of about half an inch in the case of the sight, so that aberrations will be reduced by using the central part of the aperture of the sight. This requires a convenient mechanism for adjusting the position of the instrument, both horizontally and vertically.

The instrument is mounted on a base which allows vertical adjustment with a coarse-pitch screw and nut, and which slides on a pair of polished stainless steel tubes for horizontal adjustment (see Figure 22). The whole assembly is mounted on a tubular mast carried on a fork-lift truck or "stacker," as shown in Figure 23. Two fork lifts would be desirable for working on the top stations. If only one is available, the sight must be set and left undisturbed while the gun is adjusted. A low mast with a tripod base is used for the lower turrets, where two fork lifts would interfere with one another.

A triple mirror is mounted behind the sight to reflect, through an angle of exactly 180 degrees, the collimated image of the sight reticle, so that it can be observed with the telescope. The tip of the glass pyramid is ground off and polished so that an observer can aim the sight while it is in place.

A plane mirror is mounted perpendicular to a boresight mandrel which is set in a collet in the muzzle of the gun. Rays normal to the mirror are then parallel to the bore.

6.2.3 Procedure

Four men constitute the most effective crew, but the work can be done by three men. The wire is stretched on the ground near the aircraft, extending somewhat beyond each of the two stations which are to be harmonized. An instrument is located in front of each station, and is adjusted over the wire. Each instrument is leveled and its azimuth is adjusted until a single image of the wire is seen in the right-hand telescope. The two instruments are now parallel. The triple mirror is placed behind the sight and the operator aims the sight at the objective of the left-hand telescope. The observer can then see the dot of the sight reticle in the field of view. He directs the sight operator to turn the sight until the dot is centered on the reticle of the harmonizing instrument. At the same time, the boresight mirror is placed in the muzzle of the gun, and the gun is directed to-

ward its instrument by gentle tapping until the operator of the instrument sees the bead on the objective centered on the recticle (see Figure 24). If the two instruments have been previously adjusted to agree in azimuth and in elevation, the gun and sight will now be parallel, and the usual electrical adjustments described in the TO can be carried out to complete the harmonization procedure. The MIT report[2a] describes the details of the various steps that should be taken in order to arrive at the final settings of the two instruments, the sight and the gun, in the minimum of time.

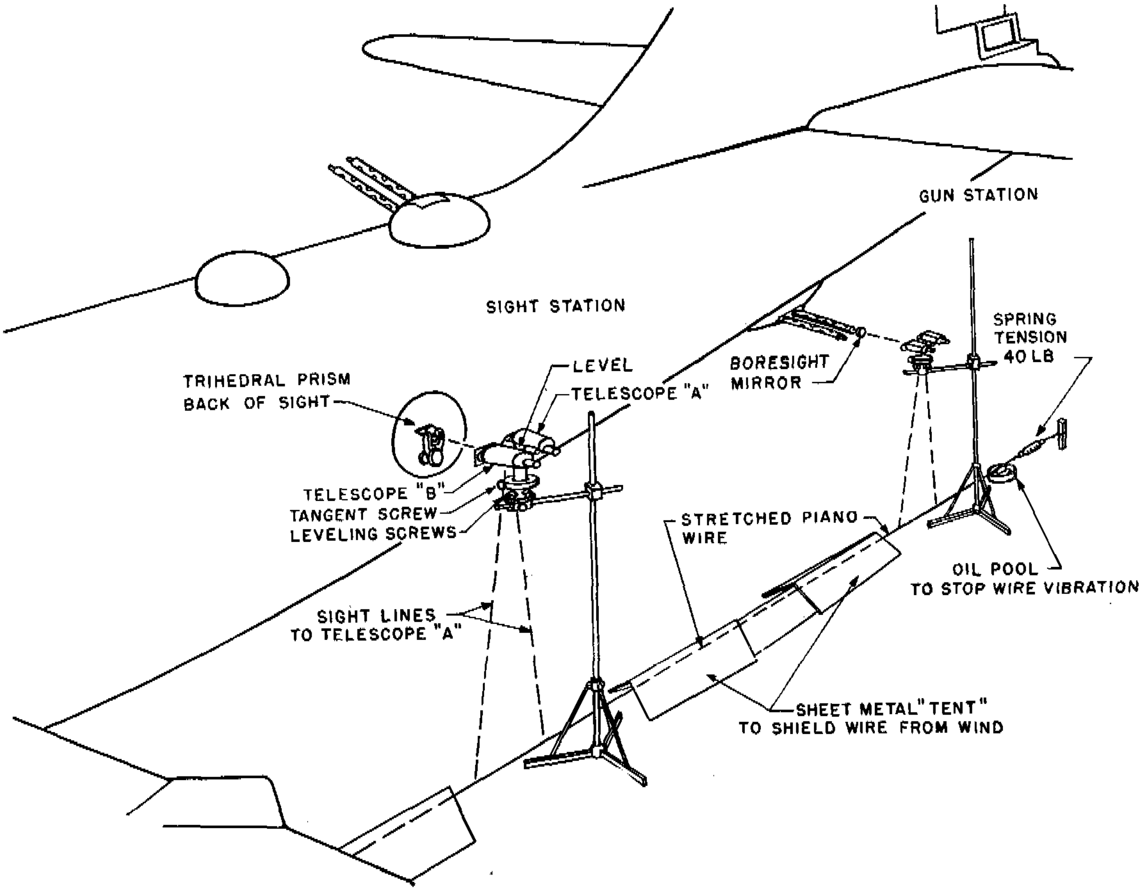

FIGURE 18. Principle of the wire method.

6.2.4 Tests of the Wire Method

Tests at Bedford were conducted in April 1945 with Mark I equipment and in August 1945 with Mark II equipment. During the latter tests, the same group of gunnery instructors which worked on the prism method learned the wire method and made it possible to evaluate, at least in a preliminary way, the effectiveness of the method.

The overall time required by three men to harmonize the airplane completely was usually a little more than 4 hrs. The best overall time was 231 min, of which 131 min were spent on optical steps, 75 min on electrical adjustments, and 25 min on miscellaneous activities (waiting for stations to be free, etc.) not immediately related to harmonization.

The accuracy of the method was measured by making a number of separate settings of the instruments, after each of which five settings of the gun and sight were made on the instruments. The results showed that the mean deviations of indicated errors of harmonization were about 0.6 mil for successive settings of

FIGURE 19. Weight and spring at end of wire.

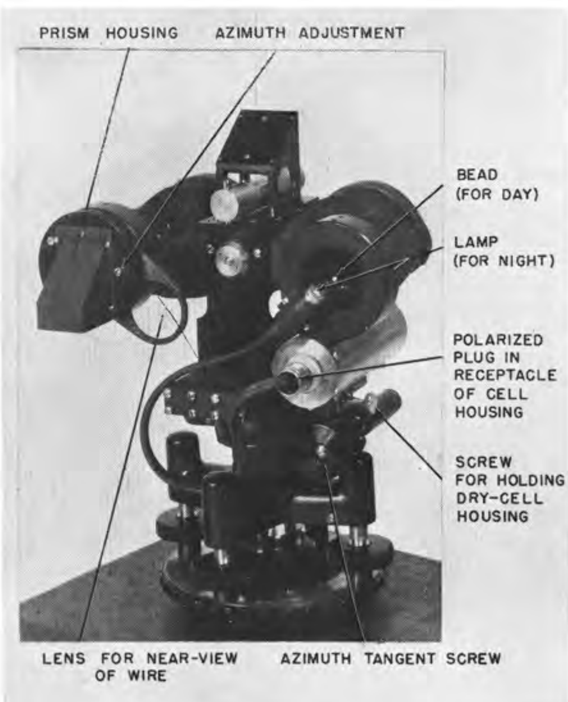

FIGURE 20. Azimuth-level instrument.

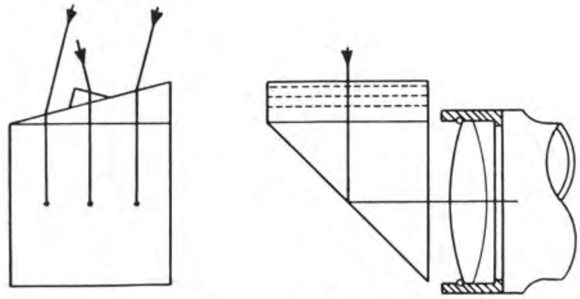

FIGURE 21. Double-image prism.

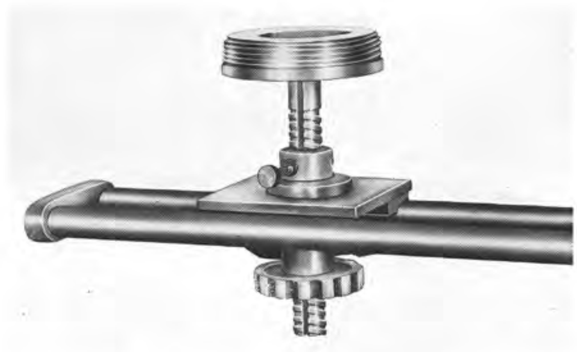

FIGURE 22. Support for azimuth-level instrument.

FIGURE 23. Azimuth-level instrument on fork-lift truck.

the two instruments. Individual settings of the gun and sight on the instruments showed mean deviations of only about 0.2 mil.

6.2.5 Discussion

The wire method appears to meet all requirements of a satisfactory method for field harmonization, as to accuracy, speed, and space re-

FIGURE 24. Adjusting gun with boresight mirror.

quired. The weight of the equipment is greater than that used with the prism method, but it is not excessive. Fork lifts are standard equipment and can undoubtedly be made available at any base in a reasonably short time, if they are not already available.

Six sets of equipment were produced in July and sent to the Marianas in August 1945, with twelve men trained in its use.

Many improvements in the equipment can still be made. The support for the instrument in the Mark II model is much better than in Mark I, but it should be even more rigid. A simple but stable tower which would support the instrument at any height up to 15 ft above the ground would be preferable to the fork lift.

6.3 THE WIRE METHOD, MARK III

6.3.1 Purpose

The Mark III equipment was developed by Merrill Flood and Associates[4] while MIT was engaged in completing six sets of the Mark II equipment for overseas shipment at the earliest possible moment. The purpose was to make such changes as seemed likely to lead to greater speed and simplification in operation, to increase the accuracy if possible, and to eliminate the need for the use of a fork lift.

6.3.2 Equipment

The instrument was based on standard 6x30 binoculars (Ordnance M13A1). Two changes were made in comparison with Mark II. The beam-splitting prism was replaced by a 50-degree prism (see Figure 25). The isosceles faces of this prism bring together two beams separated by approximately 83 degrees. It was expected that this would increase the accuracy of setting in azimuth on the wire. The telescope

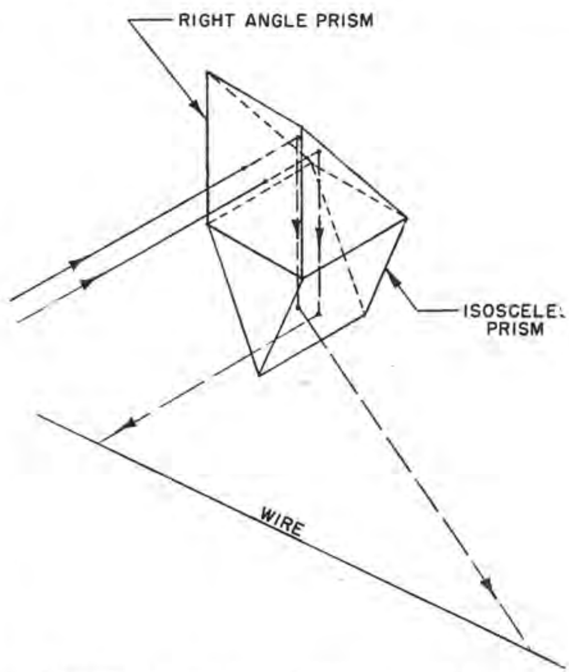

FIGURE 25. 50-degree beam-splitting prism.

on the left side was converted into a collimator with cross wires at the focus for infinity (see Figure 26). These were illuminated in the daytime by reflected sky light, and at night by electric illumination. The triple mirror was eliminated, and the operator at the sight made the

[redacted]

setting directly on the collimated cross wires.

A translation device was developed which provided smooth motion of the instrument over a range of several inches laterally on rollers with a quick acting clamp that caused no significant rotation of the instrument (see Figure 27).

A high stand, in the form of a tower made of aluminum sections bolted together and mounted on wheels, was designed and constructed to carry the translator and instrument (see Figure 28). The translator runs on rollers between tubular guides up to 15 ft above the ground. The front of the tower is entirely open so that the view is not obstructed at any level. Bracing at the sides, nevertheless, makes the

FIGURE 26. Harmonization collimator.

tower extremely rigid. Two translators, each carrying an instrument, can be mounted on the guides at the same time. This is convenient when harmonizing two stations, one of which is almost directly above the other. The tower is hinged on its base, so that it can be lowered to pass under the wing of the B-29. There are four wheels, arranged to run sideways along the wire. A yellow stripe on the base shows approximately the proper location with respect to the wire. Four screw jacks take the weight off the wheels and level the stand when it is in the proper position. Level bubbles are mounted on the base for this purpose. The observer climbs to the required height with one foot on each of two diagonal ladders, resting his back against a flat vertical board placed at a convenient distance behind the ladders. This position of the observer has been found to be entirely comfortable for observing. It seems likely that a tower of this general type offers a promising solution to the problem of locating the observer and his instrument securely at any height up to that of the highest stations on the B-29, without special machinery such as is involved when a fork lift is used.

A low stand, allowing the translator to assume any position up to about 7 ft above the ground, was also developed (see Figure 29) for use with the lower turrets.

Four wires are used, varying from 50 to 90 ft in length. A reel case (see Figure 30) has been developed to carry six wires (three 90 ft long and three 50 ft long) in such a way that they can be conveniently pulled out and rewound without becoming snarled. Errors due to wind are not serious if the wind velocity does not exceed 10 mph on the ground.

The equipment for the wire method Mark III was delivered to the Armament Laboratory at Wright Field in November 1945.

6.3.3 Procedure

Five men carry out the harmonization procedure. They are divided into two crews of two men each and a crew chief. Two high stands are used. One of these is provided with two translators and two collimators; the other with one of each. One low stand with a translator and collimator is required. Two low-power Galilean telescopes are provided to facilitate sighting. Two standard J-2 boresights and the usual harmonizing tools are required.

The wire method Mark III is not intended to be used in harmonizing the upper two turrets to the ringsight, since tests have shown that this can be done very effectively with the mirror boresight method (see Section 6.4).

A detailed procedure for carrying out the harmonization of a B-29 airplane in the minimum of time has been worked out and is de-

[redacted]

scribed in the MFA report.[4a] The locations of the wires and stands for the successive steps is shown in a diagram in this report.[4b] These details will not be reproduced here since they are not necessary in order to understand the general features of the method.

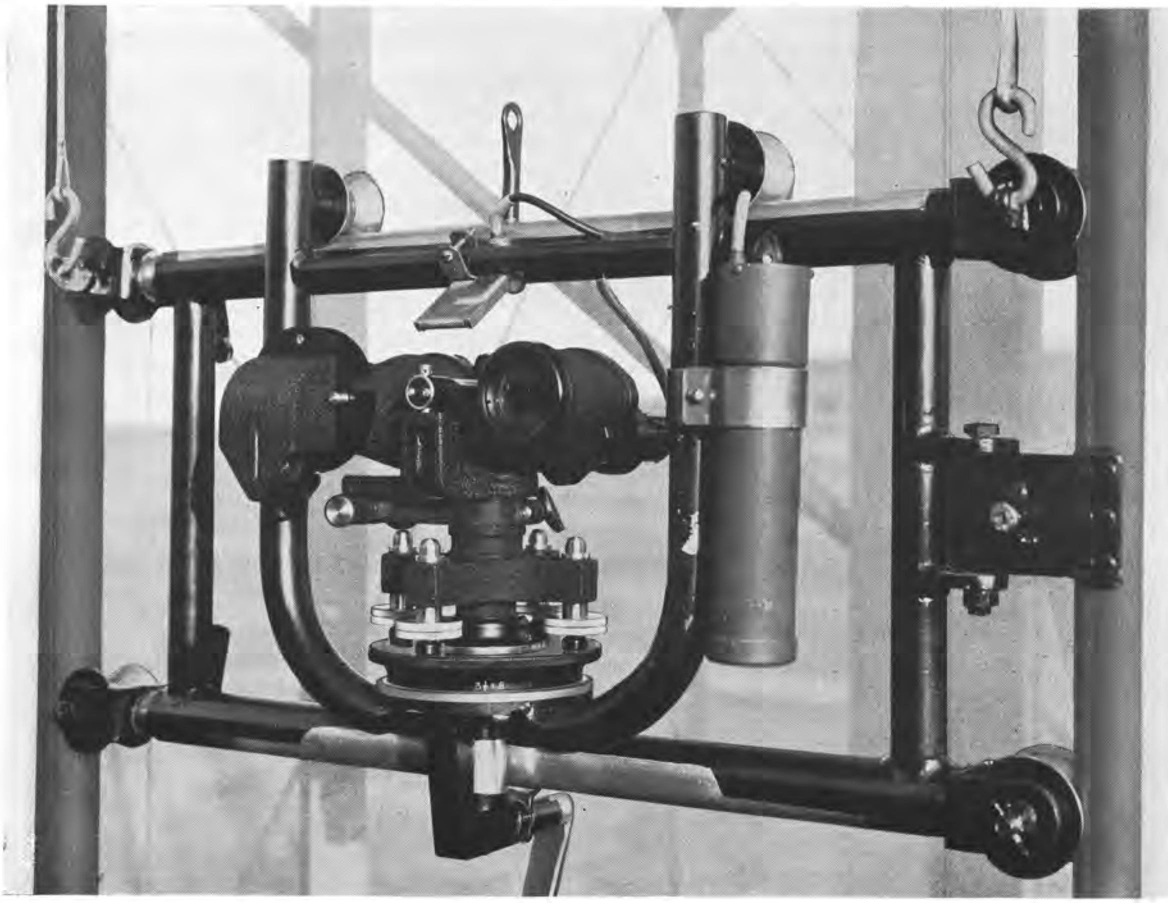

FIGURE 27. Harmonization collimator on translator.

6.3.4 Tests of the Wire Method, Mark III

The equipment was tested at Bedford in October 1945 on a B-29 aircraft with a crew of five enlisted men who had had previous experience in gunnery, but not in harmonization. Time was extremely limited, so that it was not possible to carry out the full program that had been planned. It was demonstrated, however, that the equipment was generally satisfactory. While in many respects it was superior to that of the wire method, Mark II, a number of points need to be changed.

The overall accuracy of optical harmonization between two stations was about 1.0 mil in azimuth and 0.5 mil in elevation. The accuracy of harmonizing two stations on the middle distance yards appears to be about the same. The mean deviations of individual settings in azimuth on the wire with the 50-degree prism were less than 0.2 mil.

6.3.5 Discussion

The wire method, Mark III, represents a definite advance in the development of harmonization equipment as compared with earlier equipment for the wire method. Tests

have shown that if the use of a fork lift is not regarded as feasible and satisfactory, a tower can be designed to locate the observer and his instrument at the required places. It seems likely that the final solution lies in this general direction whenever irregularity of terrain makes the use of the prism method impractical. Much more comprehensive tests are needed to provide a basis for making further changes in the Mark III equipment. Those changes that

FIGURE 28. High stand.

seem indicated on the basis of present experience are outlined in the MFA report.[4c]

6.4 THE MIRROR BORESIGHT METHOD

6.4.1 Purpose

The *mirror boresight method* was developed to simplify harmonization of the two upper turrets of the B-29 to the ringsight. These stations require high stands when the wire method is used, and if the prism method is used the field prism must be located at a distance from the aircraft which may be impractical under some conditions of terrain. The mirror boresight method also saves much time, since the necessary equipment can be installed very quickly. Moreover, it avoids harmonizing through the bad part of the Plexiglas in the upper dome, which is inevitable when the wire or prism method is used.

6.4.2 Equipment

The mirror boresight is a unit consisting of a small flat mirror mounted accurately at right angles to a mandrel which fits the usual collet in the bore of the gun (see Figure 31). The mirror faces backward, toward the breech. The center of the mirror is offset about 8 in. from the bore so that when it is inserted in a gun of the upper forward turret it can be seen from the ringsight, over the top of the turret dome. A white target is clamped over the front aperture of the ringsight. This target has a hole in its center for sighting. Two small electric lamps are mounted on either side of the hole to aid in sighting when reflections on the outside of the Plexiglas dome make visibility of objects inside difficult.

6.4.3 Procedure

The mirror boresight is inserted in the muzzle of the right-hand gun of whichever of the two top turrets is to be harmonized (Figures 32 and 33). Control of the turret is established for the ringsight and the power is turned on. The gunner moves the gun until he sees the reticle disk reflected in the mirror. If the gun is elevated as much as possible, while the reflection of the reticle disk on the upper part of the mirror is still held, Plexiglas errors will be reduced. If there is no error of harmonization, the reticle dot will be seen midway between the two lamps on the target when the observer looks through the hole in the target. If this is not the case, harmonization may be carried out under power, or else the gun may be moved to the correct position with the power off and then the selsyns may be adjusted to give zero signal in this position.

If the harmonization is badly out of adjustment, the reticle dot will not be seen in the mirror when the power is first turned on, particularly in the case of the upper forward turret which is separated from the sight by a considerable distance. The reflection, however, can usually be located easily by moving the sight so that the dot moves around the mirror in a widening spiral, with the power on.

6.4.4 Tests of the Mirror Boresight Method

Tests were carried out at Bedford in October 1945, but it was not possible to make accurate studies of time and accuracy. There was every indication, however, that the method is extremely fast, easy to learn, and accurate. The precision of a single setting appears to be considerably better than 0.5 mil. The only difficulty encountered was that the sighting lamps were not bright enough when full sunlight was falling on the dome.

FIGURE 29. Low stand and high stand.

6.4.5 Discussion

There was general agreement that the mirror boresight method is the method of choice for harmonizing the upper turrets. It saves much time and effort which would be necessary if the instruments for the wire method were used on high stands for these high stations, and it reduces the space which would be required if the prism method were used. Moreover, since a single setting is made by the sight directly on the gun without the intervention of two instruments, each of which must be separately set in the case of the wire and prism methods (four settings in all), it is obvious that the overall accuracy should be greater. The use of a better part of the Plexiglas dome, as compared with other methods, is another significant advantage of the mirror boresight method.

6.5 THE MFA METHOD

Following a study of the prism method and the wire method, Mark I, Merrill Flood and Associates developed the wire method, Mark

III, and the mirror boresight method. The most effective overall method was then studied, using the method that seemed most satisfac-

FIGURE 30. Reel case.

tory for each gun to sight combination. This overall method has been referred to as the "MFA Method." It employs the wire method,

FIGURE 31. Mirror boresight and target.

Mark III, for eight of the ten combinations, and employs the mirror boresight method for harmonizing the ringsight to the upper forward turret and for harmonizing the upper aft turret to the ringsight.

The equipment and the individual steps are the same as those already described in connec-

FIGURE 32. Inserting mirror boresight in gun.

tion with these two methods. The details of procedure are outlined in the MFA report.[4a]

6.6 MIRROR FRAME FOR HARMONIZATION

6.6.1 Purpose

The mirror frame method for harmonization is based on the use of a group of plane mirrors, mounted on a rigid frame and adjusted parallel to one another, each mirror being located on the frame so that, when the frame is oriented in a specified way, it will stand opposite one of the stations. In view of the fact that such a mirror frame eliminates the need for all targets and other equipment, it seemed worth

while to investigate its practicability. This was undertaken at Harvard.[5] The principal problems were the size of the frame required and the question whether the adjustment of the mirrors could be maintained in the presence of temperature gradients in the frame.

6.6.2 Equipment

Careful consideration was given to selecting the most favorable horizontal and vertical angles for aiming the guns and sights so that the overall dimensions of the mirror frame would be as small as possible. The arrangement finally adopted is shown in Figure 34.

In position No. 1 the guns and sights are aimed 6 degrees to the right of the axis of the aircraft and 2 degrees above the axis. Five stations can be harmonized with the mirror frame in this position, with an overall width of 122 in. and an overall height of 125 in. between extremes of the various lines of sight. A periscope with a 24-in. offset must be used to raise the line of sight from the right blister sight over the right wing.

In position No. 2, behind the tail, six stations aim 6 degrees to the left and 2 degrees above the axis, and their lines of sight are included within a range of 102 in. in width and 103 in. in height. The cover of the upper aft turret must be removed to clear the line of sight.

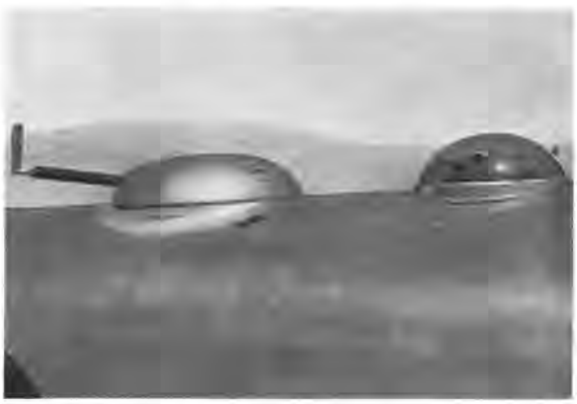

FIGURE 33. Use of mirror boresight for harmonizing upper aft turret to ringsight.

Figure 37 shows the arrangements of the mirrors on the frame. The station covered by each mirror is indicated. The mirrors are 12 in. in diameter, except for two mirrors which are 20 in. in diameter. One of these covers two stations and the other covers three stations whose lines of sight are close together. The mirrors are selected plate glass, mounted on a welded steel frame with provision for adjusting the plane of each mirror. The frame is divided into two parts which are hinged on one another for passing under the wing of the B-29 and other obstructions. The frame is mounted at three points on a standard $1\frac{1}{2}$-ton Army truck with stake body.

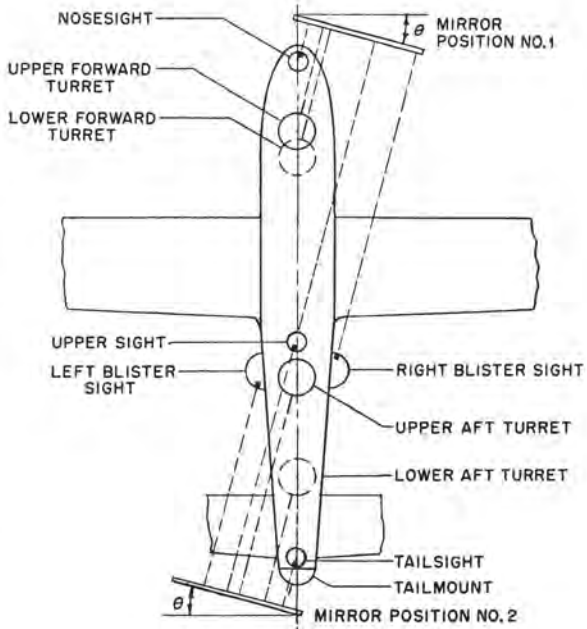

FIGURE 34. Location of mirrors for individual stations.

6.6.3 Procedure

The mirror frame is first located in position No. 1 in front of the aircraft (see Figure 38) at an angle of 6 degrees to the axis of the fuselage, with the top tilted 2 degrees toward the airplane, so that normals to the mirrors (lines of sight) were inclined 2 degrees above the axis, when looking forward. It was not particularly difficult to make the necessary setting. The truck driver was guided over the in-

tercom by an observer at the nose and by another at the upper sight. These men observed their own reflections in the appropriate mirrors and gave instructions for adjusting the azimuth of the truck until the parallax between

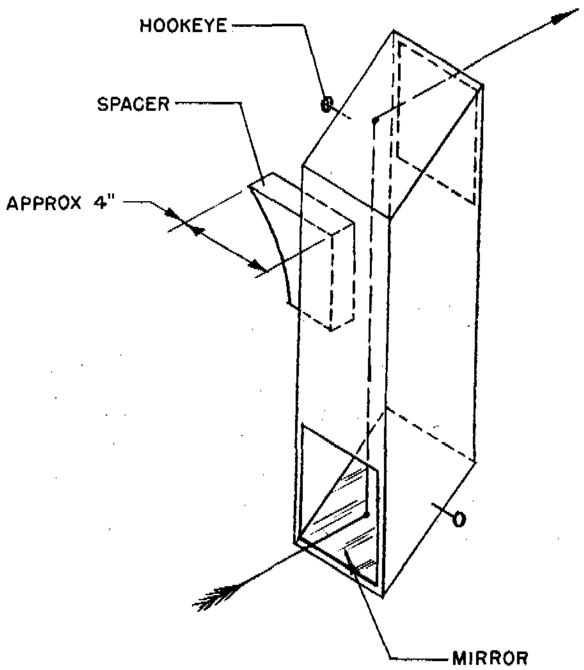

FIGURE 35. Periscope for right blister sight.

the two stations was equal to the spacing of the mirrors, so that they could both see their reflections at the same time. It then remained to adjust the tilt of the mirror toward or away from the aircraft. This was done with a jack working against the spring on the far side of the truck. The periscope for the right blister sight was attached to the side of the fuselage as shown in Figure 36. After harmonizing the five forward stations, the same mirror frame was taken to the rear of the aircraft and was located in position No. 2, as shown in Figure 39.

The mirrors were adjusted parallel to one another by using a pattern marked on the side of a building about 200 ft distant which represented in chalk the location of each mirror on a 1/1 scale. The observer placed his eye over each mark successively. If the corresponding mirror was correctly located, he would see his eye centered in the mirror. If not, an assistant would adjust the mirror in accordance with his instructions.

6.6.4 Tests of the Mirror Frame Method

The general procedure for lining up the mirror frame on a truck was tried at Bedford in October 1945. Time did not permit any actual tests of harmonization. It was shown, however, that no serious difficulties were involved in setting the frame in the proper position, and that when this was done it would be a simple matter to carry out actual harmonization with targets at the sights and guns, in the same way as at the modification centers where mirrors are now mounted on the walls of the hangars.

Preliminary tests were made to determine the permanence of adjustment of the mirrors under outdoor conditions, over a period of several days, using the marks on the wall which were first used to adjust the mirrors. Indications were that variations were less than a mil.

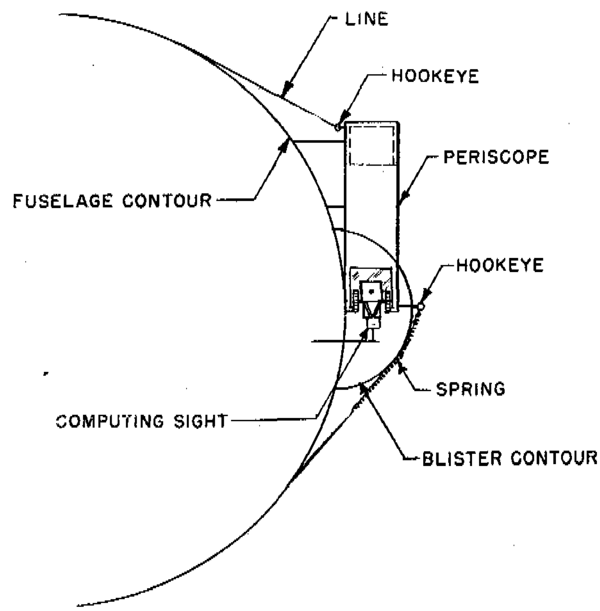

FIGURE 36. Method of attaching periscope to fuselage.

6.6.5 Discussion

The mirror frame method appears to be practical. It would be well worth while to study it further and to carry out experiments to determine variations in setting under various weather conditions.

[redacted]

A convenient way to set the mirrors and to observe variations in setting would be to observe, through a hole in a wall, a 2/1 scale pattern of the mirrors, reflected in the mirrors when they are located at any distance in excess of about 200 ft. Every mark should be centered in the appropriate mirror. A low-power telescope would be entirely adequate for making readings to about 0.1 mil if a scale were provided at each mark.

The azimuth of the truck carrying the mirror frame could be adjusted much more quickly if a reflex sight were mounted where the driver could watch, by reference to a selected mark on the landscape, the effect of turning the wheels and running slowly forward and backward as in parking. This would prevent him from overshooting the desired setting, which is all too easy to do with a truck which responds quickly to the wheel. A still better plan would be to provide for rotating the frame through several de-

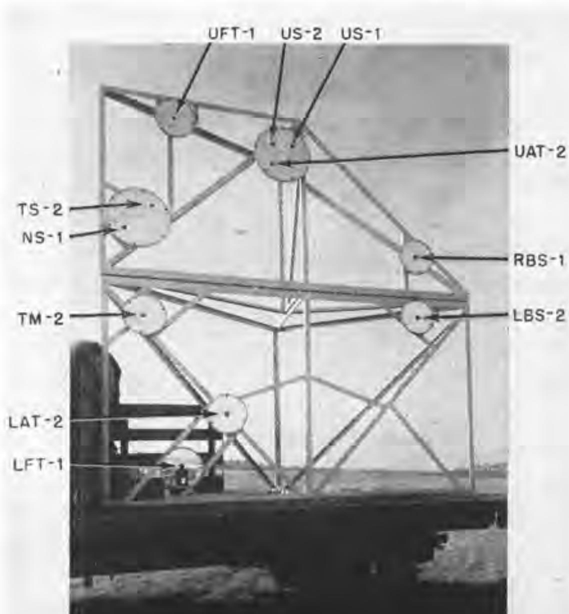

FIGURE 37. Mirror frame for harmonization.

grees on the bed of the truck, and also to provide for adjusting the level of the frame on the truck so that the jack could be dispensed with.

It should be noted that the grouping of mirrors suggested in Figure 34 and provided on the frame shown in Figure 37 ties the forward stations to the after stations only through the ringsight. This means, for example, that the right blister sight and the lower aft turret are tied together indirectly through the ringsight.

FIGURE 38. Mirror frame in forward position.

However, since each can be compared directly with the ringsight (not through the usual long chain of stations), this may be an entirely satisfactory arrangement. It would, of course, be possible to add two additional mirrors and to locate the mirror frame in a third position on the right side at the rear of the aircraft, so as to tie the right blister sight and lower aft turret together directly. It would probably not be possible to include the upper aft turret in the forward group of mirrors, or the upper forward turret in the after group, since the contour followers on the turrets would probably raise the guns too high at the required orientations. In any case, it seems unlikely that it will be necessary to provide further connections between the forward and after groups.

6.7 PRESENT STATUS OF THE HARMONIZATION PROBLEM

The work carried out under Project AC-127 shows clearly that it is practical to provide optical equipment capable of harmonizing B-29 aircraft with the necessary accuracy in the

[redacted]

field, in space considerably smaller than that required by the middle distance yard method.

The prism method appears to be the simplest method to learn, and it unquestionably involves lighter and simpler equipment than the wire method. It meets all requirements except when approximately level terrain to a distance of about 200 ft from the aircraft is not available, as is the case at many of the hardstands in the Marianas. The use of a 12-degree prism would improve matters, but would not solve this difficulty if there are declivities within less than 100 ft of the fuselage.

The wire method meets all requirements, including that of limited available space, but it involves heavier and somewhat more complex equipment than the prism method. There is little to choose as regards time and accuracy between the two methods. Either is entirely adequate in both respects.

FIGURE 39. Mirror frame in aft position.

The mirror boresight method is strikingly satisfactory for the two upper combinations, and should be used whenever possible for these stations. In conjunction with the wire method, it constitutes the MFA method. If used in conjunction with the prism method, it would remove the requirement for relatively level ground as far as 250 ft from the aircraft at bearing 150 or 210 degrees, when a 6-degree prism is used.

The mirror frame method has not been worked out as fully as the other three methods, but its inherent simplicity and freedom from the need for critical adjustment of small instrumental parts suggests the desirability of developing and testing it far enough to reach a definite conclusion as to its usefulness.

The present quality of Plexiglas introduces errors larger than the desired accuracy of the harmonization equipment. Every effort should be made to improve the quality of the Plexiglas, particularly in the dome for the ringsight. The Plexiglas should be removed if further definitive tests of harmonization equipment are to be carried out.

All the factors which disturb the harmonization of aircraft over a period of time are not clear. It is obvious that combat damage and rough landings will throw the level of various stations out of adjustment, and possibly even rotate them, so that releveling will not necessarily restore the harmonization. But there is little if any information to show whether there is a gradual warping of the fuselage which is sufficient to require periodic harmonization in the absence of accidents. The circular tracks on which the guns and the ringsight turn are not as rigid as they should be if harmonization is to be maintained to 1 mil.

It seems likely that one of the principal causes of the development of errors in the harmonization over a period of time in the field is gradual unbalancing of the servo-amplifier. It would seem logical to check the balance of each amplifier before undertaking optical harmonization, and then to verify the harmonization to see whether any changes in the setting of the selsyns are actually needed. It seems most unlikely that if the selsyns are set up tight they will rotate spontaneously, and so changes in harmonization should be sought elsewhere and corrected in other ways whenever possible. When turrets or sights are replaced, optical harmonization is of course required, but in most other cases it seems unlikely that it will be necessary to change the selsyn settings if disturbances in leveling of guns and sights are corrected, unless the fuselage bends over a period of time.

A question of great importance is the extent to which harmonization of a plane in flight differs from that of an airplane on the ground, resting on its landing gear. The difference is probably much greater than the 1 mil accuracy

requested for the harmonization procedure. It is of paramount importance that the difference be measured so that a systematic correction may be applied to harmonization carried out on the ground. Harmonization in the air could easily be checked by installing gun cameras with moderately long-focus lenses in the turrets tracking the sun or moon at various bearings and making several exposures at instants when the reticle dot of the sight is centered on the sun or moon. By averaging the measured positions of the images on the resulting films, and comparing them with similar measures made on middle distance yard targets when the aircraft is on the ground, it should be possible to determine the change in harmonization in flight for each station and for various bearings of the line of sight.

The effect of temperature and wind on harmonization due to bending of the fuselage should be determined by observing middle distance yard targets under varying conditions. Limited observations at Bedford have shown that when the sun shines at about 45 degree elevation in a clear sky, it causes on one side of the fuselage a separation in the line of sight of the two lower turrets amounting to about 2 mils. The effect of moderate wind on bending of the fuselage as the result of pressure on the tail and elevators is not known, but there is a definite indication that it amounts to much more than 1 mil.

Important improvements remain to be made in the equipment used for harmonization. Clamps provided with tangent screws to control accurately motions in elevation and azimuth should be designed for the sights. The present clamps are far from satisfactory. Improvements should be made in the stands and in the translator used for the wire method. The MFA translator should have its horizontal run extended by about 3 in., not only to make the location of the stand less critical, but also to make it easier to use two instruments simultaneously on the same stand when they must be located several inches apart in the horizontal direction. A boresighting telescope with about 3× magnification should be designed and put into general use as soon as possible. At present the armorer finds it difficult to make settings accurately, even on the middle distance yard targets. Magnification should markedly increase both accuracy and ease of setting.

6.8 RECOMMENDATIONS BY NDRC

1. For immediate use in the field, it is suggested that a combination of the prism method for eight stations and the mirror boresight method for two stations be adopted whenever the terrain permits use of the prism method. When space is limited, it is suggested that the MFA method be used, namely, the wire method for eight stations and the mirror boresight method for two stations.

2. A complete evaluation of the new methods should be carried out with a trained crew under the direction of a small committee made up of a physicist, an engineer, and a competent statistical analyst. Two airplanes should be available for a period of at least three months, with adequate space and shop facilities. The tests should be carefully planned to measure separately the various factors which combine to determine the overall accuracy of each method. The Plexiglas should be removed from the aircraft during these tests.

3. Further studies and developments should be carried out on all of the new methods, giving particular attention to the following:

   a. Prism Method
      (1) Determine the maximum angle (more than 6 degrees) that can be used without introducing other serious difficulties, so that the space requirements on all sides of the fuselage may be reduced to a minimum.
      (2) Make various minor improvements in equipment, including method for night illumination, means for clamping rotation of double-image prism, and other mechanical details.

   b. Wire Method
      (1) Compare use of left half of binocular as a telescope (Mark II) with its use as a collimator (Mark III) under field conditions, after making all indicated improve-

ments in cross wires, illumination, and method for focusing at close distances with Mark II. Accuracy and ease of use should both be taken into account.

(2) Improve stands and translating devices. Study advantages and deficiencies of all parts of Mark II and Mark III equipment. Develop best possible stand for convenience in operation, adjustment, and assembly. Eliminate need for the fork lift, if possible. Improve the Mark III stand by increasing width of steps of the ladder and place steps closer together. Maneuvering and assembly can be improved.

c. Mirror Boresight Method

(1) Increase brightness of lamps to facilitate sighting through plastic dome in bright sunlight.

(2) Add protection for mirror to avoid damage during use.

d. Mirror Frame Method

(1) Measure variations of setting of mirrors under extreme temperature changes.

(2) Study possible improvement in choice of angle of bearing and elevation for which the frame is designed.

(3) Complete development of periscope for right blister sight.

(4) Mount a reflex sight on windshield of truck unless adjustment in azimuth is provided for the mirror frame.

(5) Provide adjustment of the mirror frame in azimuth and elevation on the truck to facilitate settings.

(6) Study selected plate glass to determine whether it is accurate to 0.3 mil across the surface of 20-in. mirrors. If not, use Blanchard ground, polished $\frac{3}{4}$-in. plate glass.

(7) Develop best procedure for making settings of the mirror frame.

(8) Design targets for installation at sights and guns for harmonization by sighting on reflections in mirrors.

4. Study present variations in harmonization setting. Keep a harmonization log on several B-29 aircraft over a period of several months without changing any adjustment during this period. Measure (1) the setting of optical harmonization under as wide a variety of conditions as possible during the period, (2) the balance of the servo-amplifier at least once a week, and (3) the level of the turrets at frequent intervals and under different conditions. This should be done on at least two aircraft, one of which is flown often, the other held on the ground. The aim should be to separate and measure the magnitude of the following factors which affect harmonization:

a. Unbalance of servo-amplifier (probably a major factor).

b. Change in setting of selsyns (probably a minor factor).

c. Change in level of sights and turrets (probably a major factor).

d. Effect of rough landings and violent maneuvers in the air on the level of sights and turrets.

e. Effect of jacks on harmonization settings, particularly side blister sights to tail mount and to lower aft turret. Check on middle distance targets.

f. Effect of wind pressure on tail and elevators on harmonization settings. Check on middle distance targets.

g. Effect of temperature on harmonization settings. This includes effect of changing uniform temperature and also the effect of different temperature on top and bottom and right and left sides, due to sun. Check on middle distance yards.

5. Test the effect on harmonization of maintaining in good adjustment over a period of six months the balance of the servo-amplifier and the level of the sights and turrets on two aircraft, one of which is flown often, the other kept on the ground. Find out whether, if these are maintained in adjustment, it is necessary to change the setting of the selsyns, and how frequently it is actually necessary to make optical checks on harmonization. The results of this

test can be used to guide the setting up of maintenance procedures.

6. Measure the difference in harmonization setting for an airplane in flight, as compared with that for the same airplane on the ground, resting on its landing gear and jacks. Use gun cameras with moderately long focus lenses. While in flight, make exposures on the sun or moon and compare with exposures made on middle distance targets on the ground. Make observations on harmonization at various altitudes for each pair of stations at various bearings and elevations, and at various altitudes. Establish systematic corrections to be applied to harmonization settings made on the ground, so that harmonization in the air will be correct.

7. Make improvements in present standard harmonization equipment:

a. Design and make available slow motion tangent screw clamps for adjusting the setting of both pedestal sight and ringsights in bearing and elevation.

b. Develop and make available for general use a $3\times$ boresight telescope.

Chapter 7

OPTICAL FLUORITE

By *Sidney W. McCuskey and James G. Baker*[a]

7.1 INTRODUCTION

THE CONTINUOUS DEMAND on the part of optical designers for materials having unusual combinations of refractive index and dispersive power, or of peculiar transmission characteristics, has led in recent years to the development of new glasses and of large transparent crystals of several kinds. The latter include artificially grown crystals of lithium fluoride, sodium chloride, potassium bromide, and the like. These are of particular value when cut into prisms for use in infrared spectrometers. Their transmission in the red end of the spectrum extends at a high level to 29 μ (for KBr). The development of techniques for growing these crystals has already been discussed[1] and they are now made commercially by the Harshaw Chemical Company of Cleveland, Ohio.

In the design of optical systems, particularly in lenses for aerial photography, it is highly desirable to eliminate as far as possible the chromatism that remains after the lens system has been achromatized for two wavelengths. Crystalline calcium fluoride, CaF_2, has been long known as a material highly suitable for this purpose. It has a low refractive index, 1.4338, a high reciprocal dispersion (ν value), 95.4, and, more important, the ratio of its dispersion ($\sigma = dn/d\lambda$) to that of crown glass remains practically constant with wavelength. This means that a lens of crown glass and fluorite when achromatized for two wavelengths will be nearly achromatic for all.

The striking reduction in secondary spectrum obtainable by the use of a fluorite component in the optical system, however, is accomplished at the expense of less rigid tolerances in the other aberrations or else more complicated designs. This limits its usefulness in wide-field systems, since in all probability lenses with aperture ratios greater than about $f/8$ cannot be fully corrected. Furthermore the low index of the material introduces difficulties into the design. For telescopes and collimators, however, the elimination of color is most impressive. The design of camera lenses and collimators incorporating fluorite elements is described in Chapter 1.

Large natural crystals of CaF_2, sufficiently transparent for optical purposes, are exceedingly rare. Since camera lenses for aerial photography usually require disks 3 to 6 in. in diameter, the only alternative if fluorite is to be used is to grow satisfactory crystals in the laboratory.

The success of the Crystal Laboratory at the Massachusetts Institute of Technology [MIT] in growing large single crystals of LiF led the NDRC in 1941 to seek their help in developing methods for growing fluorite crystals of large size, under Project AC-11. During the ensuing four years, under Contract OEMsr-45, satisfactory methods for growing crystals as large as 6 in. in diameter were developed. Figure 1 shows some of the crystals grown in the laboratory. About 1,100 specimens of various sizes were made. Although the homogeneity varied somewhat, and although the majority of the crystals were not single, many disks 4 in. in diameter were made into excellent components for aerial camera lenses. Large prisms for infrared spectrographs were made from two of the crystals.

In the method developed under contract OEMsr-45,[2] artificial fluorite crystals are grown in a low-pressure atmosphere by controlled upward freezing of nearly pure molten CaF_2. The charge of raw material is obtained from carefully selected and graded natural fluorspar. A small quantity of PbF_2 is added to the melt to prevent contamination by hydrolysis. With proper adjustment of the scaveng-

[a] Warner P. Swasey Observatory of the Case School of Applied Science, and Harvard College Observatory. Dr. Baker is responsible for compiling the section of this chapter entitled, "Optical Applications of Fluorite."

ing agent, deleterious reaction products and the excess PbF_2 leave the melt by volatilization prior to crystallization. At times the melt is obtained from a chemically synthesized CaF_2-PbF_2 mixture. The melting point of this charge is about 1400 C.

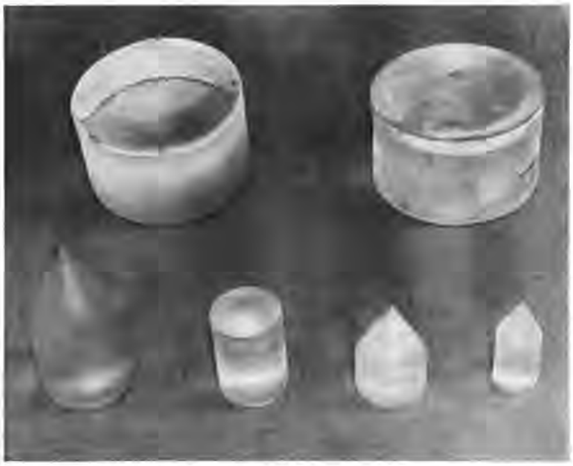

FIGURE 1. Artificial optical fluorite crystals grown in elevator furnace. (The larger crystals are 4 in. in diameter.)

Freezing takes place in a thermal field designed to produce an effective temperature gradient through the melt layer which is in contact with the advancing crystal surface. The freezing is controlled by moving the charge through the thermal field in the direction of decreasing temperature in an elevator furnace, or by changing the field in a pot furnace. Departures from the thermal field conditions theoretically most suitable for the growing of single crystals lead to multiple crystal formation, entrapped bubbles, and poor crystallographic structure.

The *effective temperature gradient*, which exists in the melt at the liquid-solid boundary, and which is normal to this boundary, controls the crystal growth in the following ways:

1. It insures that all parts of the melt are at temperatures exceeding the highest to be found in the solid. New crystalline structures cannot originate at any considerable distance within the melt, hence the chance of multiple crystal production is minimized and the resulting single crystal grows continuously.

2. The effective temperature gradient produces confusion at the advancing surface of the crystal by thermal bombardment. Deposits of impurities are thus dispersed and the resultant crystal structure is more uniform.

Closely interwoven with the effective temperature gradient in controlling the character of the final crystal is the *working speed*. This is defined as the rate at which the solid is permitted to increase in volume. It is closely connected with the time required for diffusion and for latent heat removal. *Spontaneous speed*, defined as the rate at which freezing would take place if it were not held in check, is approached when the rate of cooling is increased beyond a maximum permissible value, which obviously depends on the surrounding temperature. For a given crystal size and temperature gradient there is a critical speed beyond which control of crystallization is lost. When this takes place the inclusion of impurities and other defects is to be expected. Temperature fluctuations have the net effect of increasing the working speed. In the extreme, they can result in an actual working speed approaching the spontaneous value even though the average speed, expressed in terms of mass per unit time, is numerically below the allowable maximum.

The first crystals grown by the method outlined were found on occasion to possess three major defects, namely, color, multiplicity, and a large amount of light scattering. The removal and control of these defects may be summarized briefly.

Color. Objectionable color in the crystals grown early in the project was found to be caused by careless selection of raw fluorspar stock, by presence of air leaks in the furnace housing, and by improper design of the heater and baffling system. The latter caused insufficient ventilation of the charge during crystal growth.

Yellow, orange, red, and brown crystals resulted from colorless stock when appreciable leaks existed in the furnace, even though the pressure was kept low by fast pumping. Impurities in the stock likewise were found by experiment to give rise to deeply colored, muddy crystals. Of forty crystals ($\frac{3}{4}$-in. diameter) grown finally from practically colorless stock in an improved furnace, only three were notice-

[redacted]

ably colored. Two of these colored specimens were traced to faulty stock and one to poor vacuum in the furnace.

Multiplicity. Impurities in the natural fluorspar also resulted in multiple crystal growth. By properly designing the furnace, including crucible and seat, and by careful control of the operating temperature during the beginning of the crystallization, the yield of single crystals was increased considerably.

The operating temperature at which crystal multiplicity was least likely to appear was considerably lower than that which favored the high degree of purification required by the CaF_2 stock. Experiment showed, however, that the temperature could be increased, after the crystal had been well started, without inducing multiplicity.

When the rate of crystallization was reduced by a factor of 4, it was found possible to grow essentially single crystals in every trial. Four single crystals 4 in. in diameter were produced in four trials. The crystallization of each required a week.

Light Scattering. The scattering of light within a crystal is very detrimental to its use in an optical instrument. Much effort was expended, therefore, in overcoming the rather serious scattering which appeared in the first crystals grown.

The directional selectivity of the scattering particles suggested that they were oriented in definite crystallographic directions. Microscopic examination verified this and also revealed the hexagonal outline of the particles. Since the particles were observed in the 111 planes, and because the hexagonal outline could be derived from an octahedral specimen of CaF_2 by cleavage through one of these planes, the conclusion was drawn that the particles were thin negative crystals, perhaps containing gaseous or solid impurities. Concentration of the scattering particles near the top of the crystal as well as in the "grain boundaries" of some multiple specimens confirmed this view. Numerous subsequent observations with the petrographic microscope led to the conclusion that the impurities involved are substances such as CaO and BaS. That the anions were responsible for the ex-solution was shown by adding known amounts of different compounds to high-quality melts. As little as 0.1 per cent of CaS produced a marked increase in scattering, for example, whereas 1 per cent of BaF_2 produced no noticeable effect.

In order to remove the deleterious light scattering, a scavenger was introduced. After careful consideration, PbF_2 was selected as a scavenger and the following reactions were predicted:

$$
\begin{aligned}
PbF_2 + CaO &= CaF_2 + PbO \\
PbF_2 + CaS &= CaF_2 + PbS \\
PbO + C &= Pb + CO \\
2PbS + C &= 2Pb + CS_2
\end{aligned}
$$

Tests were made with varying percentages of PbF_2 with the result that 1 to 2 per cent of the scavenger was sufficient to free the crystals from light scattering. The following contaminants were introduced in varying percentages from 0.01 to 1: SrF_2, BaF_2, CaO, $CaSO_4$, CaS, SiO_2, Fe_2O_3. In all cases the light scattering in the crystal was reduced to a negligible amount. Further details concerning these and related experiments are given elsewhere.[2]

7.2 EXPERIMENTAL PROCEDURE IN CRYSTAL MANUFACTURE

7.2.1 Preparation of the Stock

Natural Fluorite. Two types of raw material have been used in the production of CaF_2 crystals, namely, natural fluorite and synthetic CaF_2. Natural fluorite is a moderately hard, glassy, transparent or translucent mineral occurring most abundantly in ore deposits and sedimentary formations in close association with other minerals. The Illinois-Kentucky region of the United States and a small area in New Mexico are two of the finest fluorite producing areas in the world. The mineral commonly occurs in crystalline masses ranging in color from water white to black.

As the material comes from the mine it contains varying amounts of impurities such as calcite, barite, silica, galena, and clay. Since only the best of CaF_2 stock can be used successfully for synthetic crystals, a field survey project was established in August 1942 under Contract OEMsr-563 with Princeton Univer-

[redacted]

sity,[3] to discover sources of raw fluorspar suitable for synthesis. As a result of the survey, ore from both the Babb-Frazer mine and the Aluminum Ore Company mines in the Illinois-Kentucky district, and from deposits near Duncan, Arizona was judged suitable for the purpose. Approximately 5 tons of good grade ore were shipped to MIT.

Extreme care must be exercised in selecting fluorspar for recrystallization. Only clear colorless material can be used. The larger pieces are broken into ¼-in. pieces and immersed in water. Clear pieces are then readily distinguished from those with minute solid inclusions which are rejected. The selected pieces are washed with water to remove surface clay and any soluble salts, and are rinsed twice with alcohol to remove the water. Finally the fluorspar is pulverized in a mineral crusher and stored in stoppered clear glass jars. This material is scavenged with 2 per cent PbF_2 just before it is loaded into the crucible.

Chemically Prepared CaF_2. On June 1, 1942, a special study was undertaken to determine to what extent it was feasible to synthesize the required raw material in the event that the natural fluorite supply became inaccessible or poor in quality.

Only the highest grade chemical reagents were used in the synthesis of CaF_2. In several instances it was necessary to repurify the reagent. Commercial aqueous HF solution was redistilled in a platinum still. $Ca(NO_3)_2$ was made in a way designed to eliminate as far as possible the impurities known to be contained in the calcite crystals which serve as the source of Ca^{++}. The details of this chemistry are given elsewhere.[2]

In the first syntheses of CaF_2, the mixing of the reagents $Ca(NO_3)_2$ and NH_4F was brought about by slow diffusion.[4] After the solutions had stood for several days, small crystals of CaF_2 began to form in and around one of the dishes. These were coarse dendrites made up of tiny cubes piled on one another. The process required so much time, however, that it was rejected as impractical.

Titration experiments were made in which dilute NH_4F solution was allowed to run slowly into dilute $CaCl_2$, while at the same time an equivalent amount of more concentrated $CaCl_2$ was added. The milky precipitate which formed was far from crystalline. Final large scale titration trials yielded completely erratic results. Even with minor changes in concentration, acidity, or treatment, the products varied widely in appearance. Efforts to crystallize the material in the furnace were unsuccessful in spite of the fact that spectroscopic analysis showed the synthetic CaF_2 to be equal in purity to the natural fluorspar.

The use of PbF_2 as a scavenger when mechanically mixed with these same synthetic products was not successful in preventing light scattering in the crystal. The dendritic character of the precipitate apparently hindered the removal of last traces of water during the preparation, and rapid preliminary evacuation prior to heating was obstructed. By co-precipitating CaF_2 and PbF_2, however, a more intimate mixture of the scavenger with the CaF_2 was obtained and a satisfactory crystal material resulted.

Since the synthetic mixtures of CaF_2 and PbF_2 when co-precipitated and crystallized resulted in a product equal to that obtained with natural stock, a simplification of the synthesis was undertaken. The procedure developed for the preparation of a fine powder containing 2.5 per cent of PbF_2, and having a density about half that of natural fluorspar, is as follows: To an aqueous suspension of cp calcium and lead carbonate powders in a lead receptacle, is added aqueous cp hydrofluoric acid in excess. The precipitate is washed by decantation, dried over a steam bath, and stored in HF resistant containers. This material, being bulky, is ordinarily preheated to the melting point in a vacuum furnace, then granulated and otherwise treated as spar.

Four 1.5-in. crystals were successfully grown with this mixture of fluorides, indicating that such synthetic material may, if necessary, be used instead of natural stock.

7.2.2 Elevator Furnace Design

Vacuum Tanks. It is necessary that crystallization of CaF_2 from the melt be carried out in vacuum to prevent chemical reaction of

[redacted]

the stock and other materials present in the furnace. Thus each furnace consisted of a steel or heavy brass tank with heavy bottom flanges which could be fitted into a machined base plate. The latter was tapped and bored to receive the tank flange screws, electrodes, pump connection, and other necessary items. Both externally wrapped water tubes and helically baffled water jackets were used for cooling. Figure 2 shows the upper part of one of the steel bell jars with its water-cooled window, lifting rings, and the

FIGURE 2. Upper part of steel bell jar.

soldered rectangular copper tubing wound around the cylinder. Figure 3 shows the furnace bell jar raised so that the interior positioning of electrodes and crucible is evident.

The tanks were sealed to the base plates by either lead antimony gaskets compressed within the tank flange grooves or by rubber gaskets squeezed between plane metal surfaces. The latter were found to be very satisfactory when kept cool. Machine screws maintained compression between tank flange and base plate.

Dimensions of the tanks ranged from 8 to 16 in. in diameter and 20 to 48 in. in height, with walls from $\frac{3}{16}$ to $\frac{1}{2}$ in. A thick disk welded to the top of each tube contained a water-cooled quartz observation window, shown in Figure 2.

The large furnaces were evacuated in about an hour to the desired pressure, 10^{-3} mm of mercury or lower, by two glass mercury diffusion pumps in series. One of these was designed for a speed of 75 liters per second, the other for a speed of 30 liters per second. A Cenco "Hypervac 20" was used as a forepump. Vacuum systems for the smaller furnaces were identical with the above except that the forepump was a Welch Duoseal Model 1405 H. An essential feature of each evacuation system is a demountable trap, whose function is to collect corrosive gases such as HF which are produced during the scavenging action of the PbF_2.

Heaters. The relatively high melting point of calcium fluoride, about 1400 C, necessitated the production of temperatures far above those ordinarily encountered in work of this kind. Since a high temperature gradient had to be maintained through the melt-crystal boundary, the maximum temperature inside the furnace was about 1600 C. All heaters were designed to keep operating potentials below values which would cause gaseous discharges.

Heaters of two types were used. The earlier ones were formed of molybdenum wire wound on Alundum grooved cores. It was found, however, that the terminal potentials with this type of heater were so high that destructive gaseous discharges occurred between hot parts in the rarefied atmosphere. Also the CaF_2 vapor attacked the Alundum core so that it deteriorated rather rapidly. This type of heater was abandoned, therefore, and replaced by helical or vertical bar type graphite heaters.

In the graphite heating elements a helix, turned on a lathe from a solid rod of graphite, is surmounted by a grid of parallel graphite bars, electrically in series. Several of the helices are shown in Figure 4. To prevent thermal field distortion due to the terminal connections, graphite rods were used in place of the conventional water-cooled clamps. These were of such diameter that their resistance heating tended to compensate for conduction losses from the heaters. Terminal contact areas were made as large as possible and their resistances were

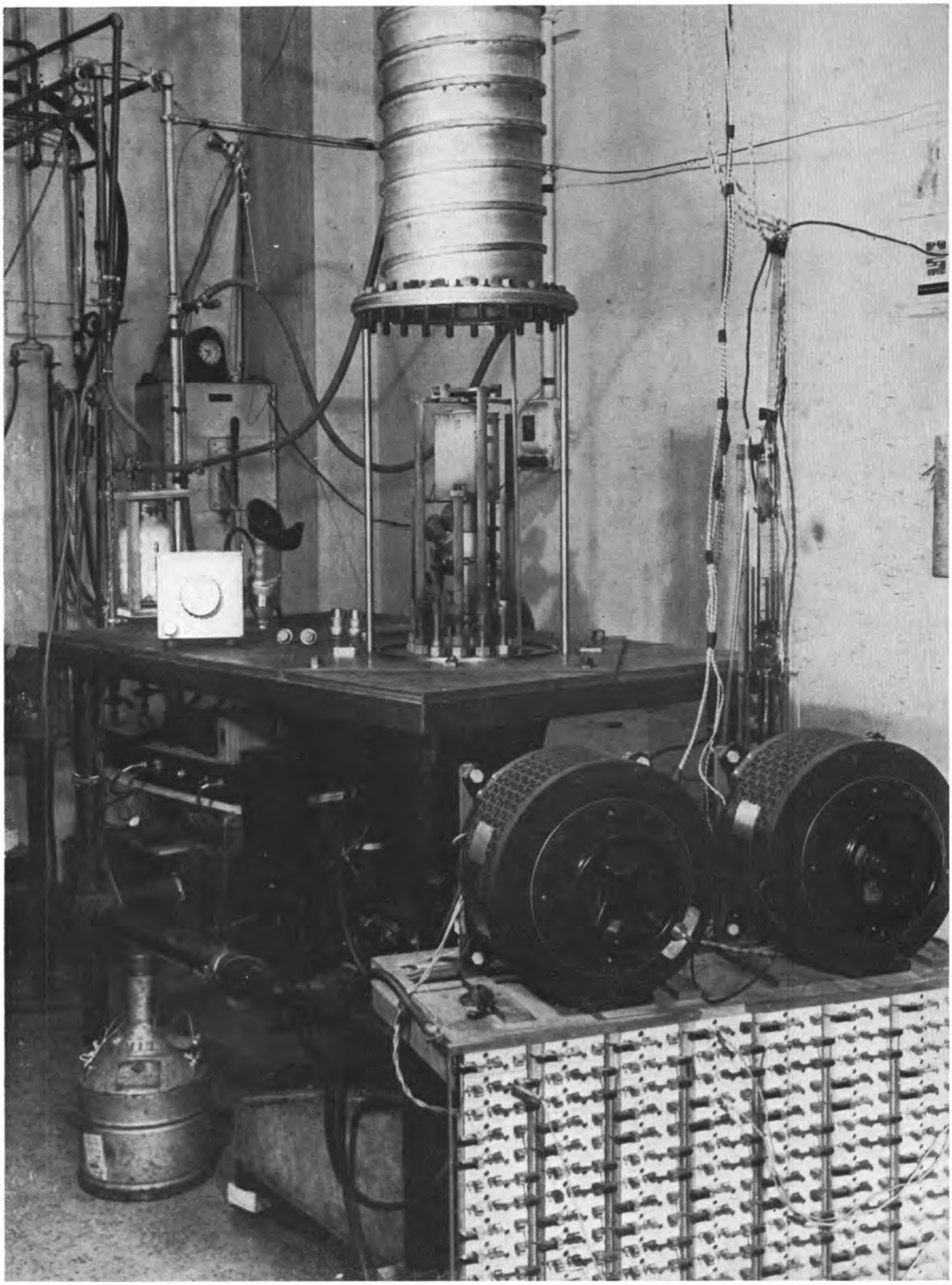

FIGURE 3. Elevator furnace with bell jar raised.

stabilized by means of shrink fits or screw threads. The rods were held by clamps attached to water-cooled electrodes in the base plate.

Figure 5 shows schematically a cross section of the elevator furnace. Positioning of heater and grid are evident from the numbered legends. Dimensions of the heater for an 8-in. furnace are representative. Helices for growing

FIGURE 4. Graphite helices used for heaters.

$\frac{3}{4}$-in. diameter crystals were $1\frac{1}{4}$ in. in diameter, separated by an annular molybdenum gradient baffle (see Figure 4, middle helix). The helices were each $3\frac{1}{2}$ in. long with wall thickness $\frac{1}{16}$ in. and were threaded with $\frac{1}{4}$-in. pitch.

Other furnaces employed a single helix (see Figure 5, for example) with cover heater in the form of a grid. In this type the separation gradient baffle previously described became the lower baffle (No. 32 in Figure 5). Such a heater proved superior to the double helix.

The machining and other fabrication difficulties led finally to the adoption of cylindrical grids with the coils running lengthwise, as shown in Figure 6. Thermal field distortions due to the low-resistance massive terminals were minimized by placing these terminals at the top of the heater where they would be as far as possible from the freezing region.

In all furnaces the system of baffles is much the same. The top baffle is a laminated circular plate supported by a graphite rod in a position directly above and close to the furnace. The laminations from bottom to top (No. 43 in Figure 5) are 0.005-in. molybdenum sheet, $\frac{1}{8}$- or $\frac{1}{4}$-in. graphite plate, and either another molybdenum or a 0.029-in. stainless steel sheet. The cylindrical baffles are composed of two sheets of molybdenum wrapped around a graphite tube and tied with molybdenum wire. Molybdenum wire is placed between the two sheets to insure the small spacing required for effective baffling. At the bottom of the crucible seat are two circular baffles of molybdenum spaced about $\frac{1}{4}$ in. apart. The gradient baffle (No. 32 in Figure 5) is a molybdenum annulus whose inside diameter is slightly larger than the outside diameter of the crucible.

At the present time no probe is provided to tell whether the crystal-melt boundary is in the plane of the gradient baffle. At this point, under ideal conditions, the heat flow lines are parallel and the temperature gradient is high. Actually the maintenance of these ideal conditions is only for short durations of time and is more or less fortuitous in the present furnaces. A comprehensive study of freezing levels and temperature control in the lower chamber of these furnaces is indicated in order to put the

FIGURE 5. Cross section of elevator furnace. (1) base plate, (2) tank, (3) base ring, (4) water jacket, (5) cap plate, (6) window tube, (7) quartz window, (8) cooling tube, (9) sealing gasket, (10) clamping screw, (11) lifting ring, (12) pumping tube, (13) elevator bushing housing, (14) gasket seat, (15) neoprene gasket, (16) thrust washer, (17) adjusting screw, (18) copper electrode, (19) mica insulators, (20) cooling chamber cap, (21) power lead binding nut, (22) electrode connector, (23) clamping ring, (24) insulated locating coupling, (25) graphite electrode extension, (26) clamping nut, (27) mica insulators, (28) insulated adapter, (29) molybdenum lower baffles, (30) graphite elevator rod, (31) spacers, (32) gradient baffle, (33) gradient baffle support, (34) crucible seat, (35) molybdenum side baffle, (36) crucible, (37) crucible lid, (38) cylindrical heater, (39) power lead baffle support, (40) graphite clamping screw, (41) heater support ring, (42) grid, (43) top baffles, (44) top baffle support plate.

[redacted]

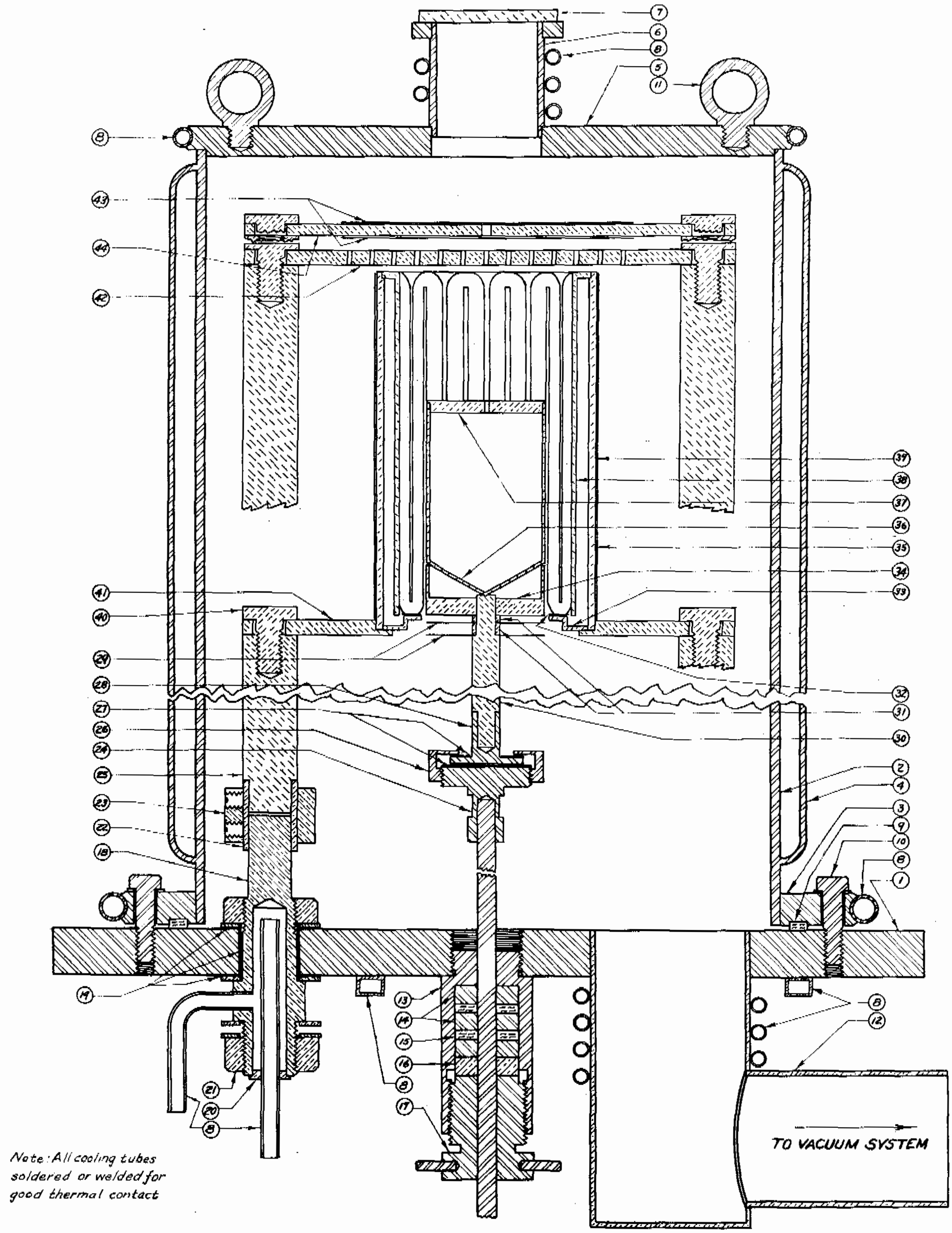

FIGURE 5

[redacted]

consistent manufacture of crystals on a firm basis.

Crucibles. Highly purified graphite crucibles were used in these furnaces. They had the distinct advantage that the crystal did not adhere to the crucible while cooling and hence strains likely to result from differential contraction were largely avoided. The crucibles were thin-walled so that thermal conduction was negligible in comparison with conduction in the fluorite melt. Otherwise the crucible contents would be more or less thermally short-circuited and maintenance of a controlled temperature gradient would be impossible.

FIGURE 6. Cylindrical heater grids.

FIGURE 7. Graphite crucibles.

The crucibles were turned on a lathe from a solid rod of highly pure, close-grained graphite. The bottoms are conical to increase the chance of forming single crystals. Wall thickness ranges from $\frac{1}{32}$ in. in the case of 1-in. crucibles to $\frac{1}{16}$ in. for those with diameters of 4 and 6 in. The angle of the cone-shaped base is 60 degrees for the smaller crucibles and 160 degrees for the larger ones. Several crucibles are shown in Figure 7.

In the elevator furnace the crucible is supported in a graphite seat, a thin-walled cylinder open at the top with a heavy bottom through which a graphite rod contacts the tip of the crucible cone. The upper end of the cone makes light contact with the top of the seat as shown in Figure 5 (No. 34). The graphite rod is an extension of a steel rod which is lowered by a gear box mechanism capable of lowering the seat at speeds ranging from 4.8 to 0.025 in. per hour. A 1 rpm synchronous motor drives this mechanism. Thus the crucible is lowered at a rate which causes proper solidification of its contents as each level passes the gradient baffle.

Power Supply. To supply power at variable low voltage to the heaters, General Radio Type 50B Variacs control the primary voltage to 7 kva transformers whose divided secondaries can be connected in series-parallel combinations. The Variacs are equipped with clutches and chain sprockets for continuous power adjustments with a motor drive. Each heater circuit has a wattmeter or ammeter or both. An overall view of an elevator furnace installation with its power supply is shown in Figure 8.

Operation. Actual operation characteristics of such a furnace may be described in terms of the record for growth of a 4-in. diameter single crystal of excellent quality. It must be emphasized that repetition of the cycle would be no guarantee of successful duplication of the crystal, but it is a typical record.

The crucible was charged with 1,600 g of good quality stock and 2 per cent by weight of PbF_2 and placed in the furnace with the crucible tip $\frac{1}{4}$ in. above the gradient baffle. The elevator mechanism was adjusted to lower the crucible through the baffle at a rate of 1 in. in 26.4 hr. Then the tank was bolted down, water valves were opened, and vacuum pumps were started.

When the pressure had reached 1 cm of mercury, liquid N_2 was applied to the trap. Power

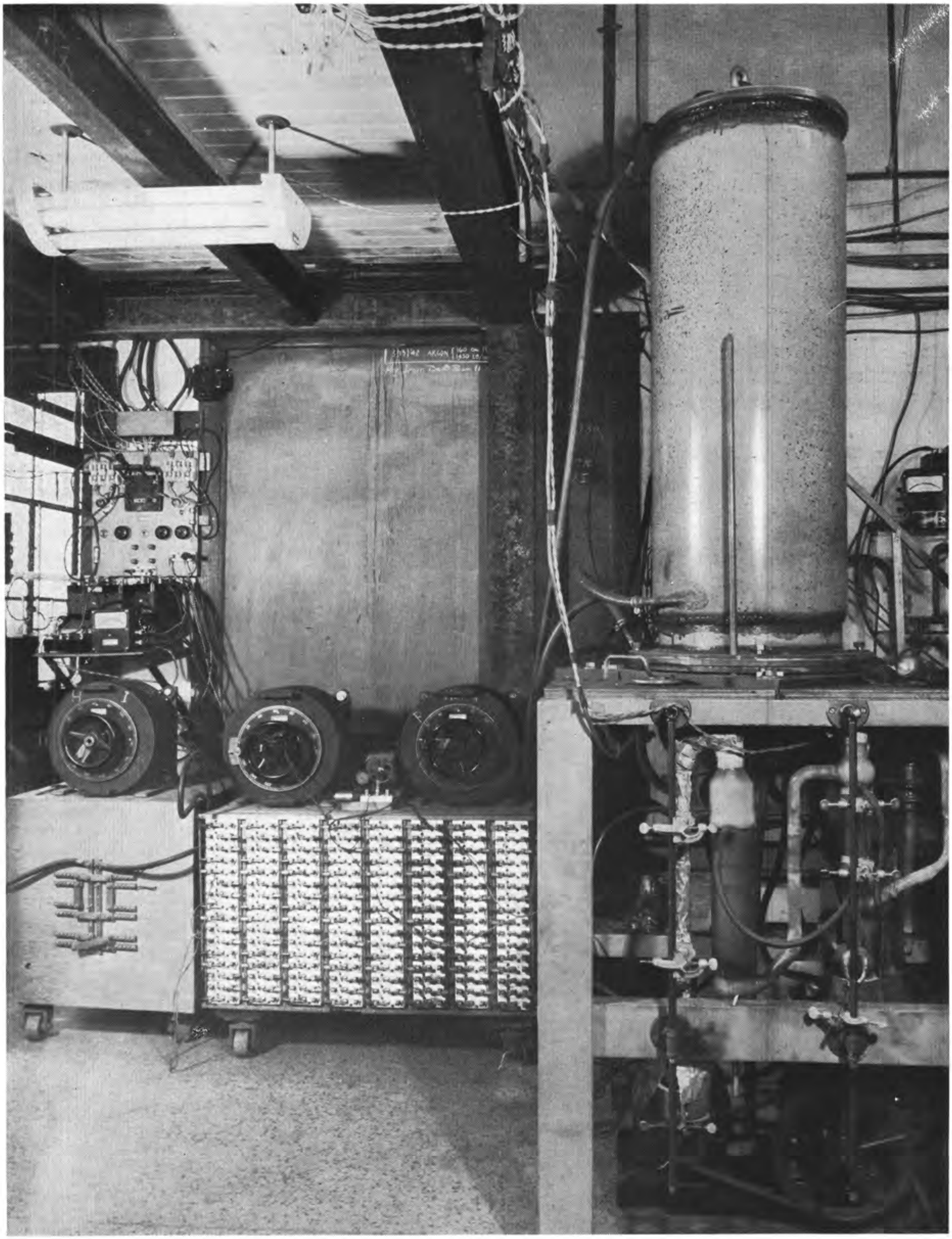

FIGURE 8. Elevator furnace installation.

[redacted]

was then supplied according to the schedule of Table 1.

TABLE 1. Power supplied to elevator furnace in one experimental run.

Time	Pressure in 10^{-3} mm Hg	Power to grid (w)	Power to heater (w)
0	0.4	1,040	2,040
50 min	1.1	1,620	2,700
1 hr 20 "	4.8	2,220	3,780
1 " 50 "	4.8	2,800	5,800
2 " 15 "	1.6	3,300	7,800
2 " 30 "	1.7	3,900	9,800

At the end of 2.5 hr the elevator was started down, at a rate of 1 in. in 26.4 hr. Approximately 67 hr later, after the elevator had traveled 2.5 in., the rate of descent was changed to 1 in. in 13.2 hr. After the elevator had traveled ⅝ in. farther it was stopped and the Variac drives were engaged to decrease the power continuously at a rate which would bring the voltage to zero in about 12 hr. Air was then admitted to the cold furnace and the crystal removed. An example of this size of crystal is the larger specimen exhibited in Figure 1.

7.2.3 Pot Furnace Design

Crystal blanks of large diameter but small thickness, such as those needed for aerial camera lenses, have been grown in a pot furnace. This type of furnace is mechanically static, the freezing of the melt being controlled entirely by regulating the power input. The temperature gradient is provided by supplying heat independently above and sometimes below the crystal. No particular advantage accrues to the use of the pot furnace other than the mechanical simplicity. For thin (1 in.) crystals this type of furnace was found to yield good results very consistently. For thicker crystals the gradient is too low for satisfactory crystal growth.

Figure 9 shows the essential parts of such a furnace. The heating element consists of a new type of grid, two spiral graphite ribbons in parallel suspended inside and at the top of the cylindrical heater. A guard ring surrounding the lower part of the crucible eliminates most of the lateral heat loss. The cylindrical heater is of the longitudinal coil type finally adopted for the elevator furnace. Its general character is indicated in Figure 9. In other respects the pot furnace resembles the elevator type.

For small pot furnaces which accommodate crucibles up to 4 in. diameter, a 7 kva transformer and General Radio 50B Variac supply power to each heater. For the larger furnaces, in which 6-in. crystals are grown, it was necessary to use several such transformers and controls. A cam and gear train decreased the power continuously at a rate which was intended to keep the crystal growth linear in time. Voltage regulators on the power supply responded to fluctuations of the order of 0.25 per cent and served to stabilize the supply to the point where the cam drive was effective.

In this type of furnace it is particularly necessary to have a probe of some kind to measure the progress of the freezing level in the melt. Such a probe was used in the largest pot furnace. A relatively rigid 50-mil tungsten wire was fastened to an iron rod ¼-in. diameter and 1 in. long. The iron rod slides smoothly in a Pyrex tube mounted at the top of the furnace tank. It was raised and lowered by an electromagnet surrounding the tube. The tungsten wire extended down into the tank through a series of coaxial holes in the top baffle, top heater, and crucible lid. Electrical heating of the passageway through the top baffle was necessary to guard against clogging by sublimed CaF_2.

Crystal growth which is linear with time is approximated by using the cam and gear train previously mentioned. The probe readings provide a record of crystal growth which serve as the basis for design of this cam. The ultimate desire in power control, of course, is to produce uniform vertical heat flow. Although many experiments have been performed to determine the proper ratio of grid to heater power, the best value still remains to be found.

The operations required to make a 6-in. crystal will serve to illustrate the procedure, time, and power involved in a typical pot furnace run. The crucible was charged with 3,000 g of good quality stock and 2 per cent of lead fluoride by weight, and was then placed in the furnace so that the tip of the crucible was approximately

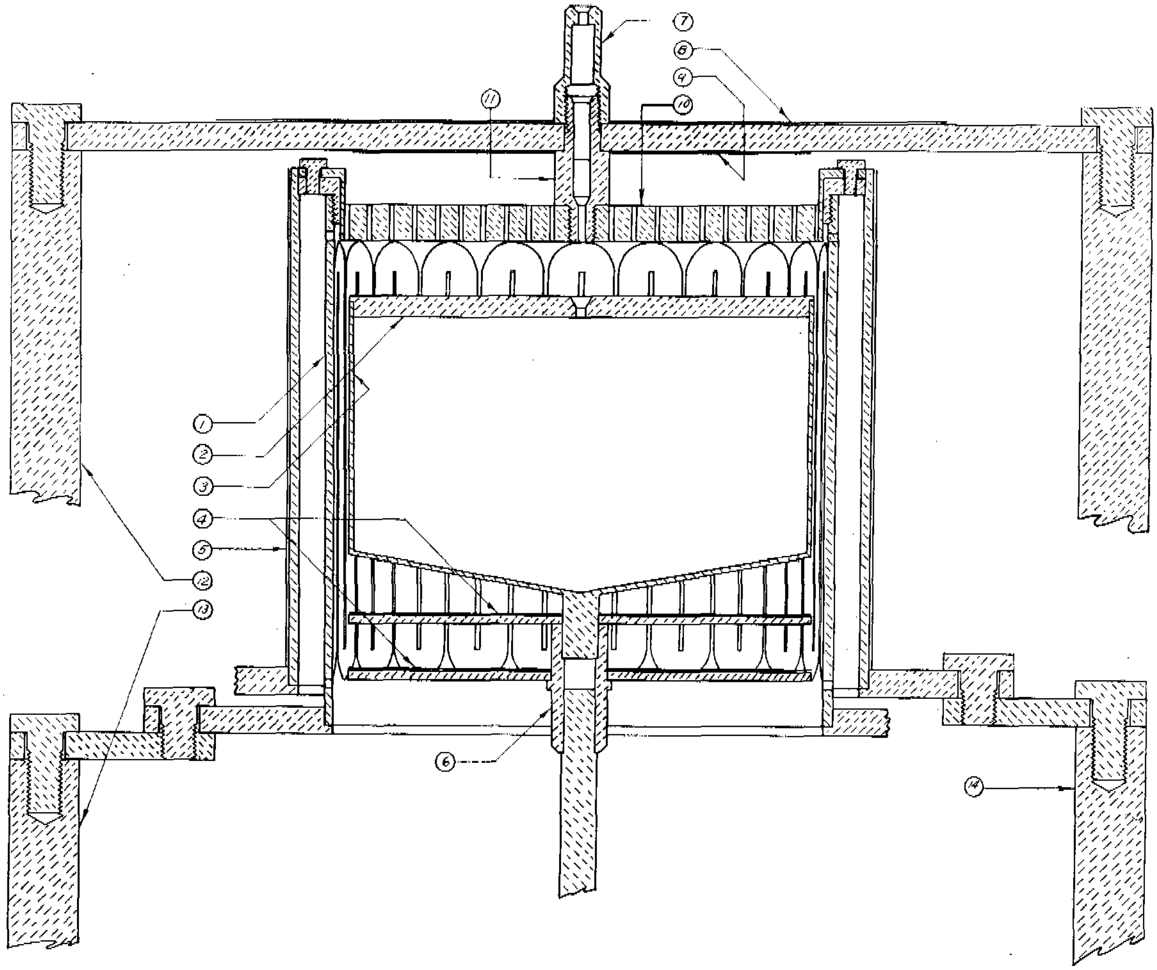

FIGURE 9. Cross section of pot furnace. (1) vertical bar type heater, (2) crucible lid, (3) crucible, (4) molybdenum baffles, (5) molybdenum cylindrical baffle, (6) crucible seat and baffle carrier, (7) grid clamping nut and probe guide, (8) stainless steel, (9) molybdenum baffle, (10) top heater, (11) connector and probe guide, (12) top heater electrode, (13) cylindrical heater electrode, (14) common electrode.

½ in. above the bottom of the heater coils. Then the tank was bolted down, the probing device installed, and the vacuum pump started. Liquid nitrogen was applied to the trap after the pressure had reached 1 cm of Hg. The power schedule is shown in Table 2.

TABLE 2. Typical power schedule for pot furnace run.

Time (hr)	Pressure in 10^{-3} mm Hg	Power input to grid (w)	Power input to heater (w)
0	1.5	1,135	960
1	1.6	2,840	2,580
1¾	7.1	3,980	3,830
2¼	7.2	5,820	5,950
2¾	3.2	9,100	7,970
3	3.1	9,650	6,520
3½	Grid power started down with cam-gear drive.		

When probe measurements indicated that crystallization was complete, the power was lowered to zero over a period of 1.5 hr. The crystal was allowed to cool in vacuum over night and was then removed from the furnace. The curve in Figure 10 illustrates the growth of the crystal as measured with the probe.

7.2.4 Annealing

Strains in crystals grown from the salt melt may, for convenience, be classified as (1) cooling and (2) locked or structural strains. The

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former evidently result from uneven or too rapid cooling through the plastic temperature range. The latter are usually associated with imperfect crystallographic structure. The usual treatment for strain is a recooling of the crystal

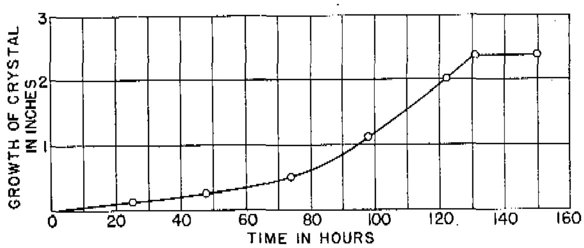


FIGURE 10. Curve of growth of crystal in 6-in. pot furnace.

through the plastic range at a speed and under thermal field conditions favorable for homogenous contraction. This annealing process often eliminates cooling strains but seldom reduces the structural strains. Faulty isothermal contours, especially during early stages of growth, incorrect ratio of growth speed to temperature gradient, and entrapment of impurities are suggested as causes of locked strain.

A special annealing furnace was designed and constructed for this work. It consists of a capped stainless steel tube $6\frac{3}{8}$ in. diameter, 28 in. long, and 0.080 in. wall thickness, which is heated along the upper third of its length. The heat source is a thermally insulated Nichrome wound Alundum core whose inside diameter is 7 in., leaving a space of $\frac{5}{16}$ in. between tube and heater. It is powered by a transformer controlled by a Variac. The voltage may be slowly decreased by a continuous drive mechanism. Through a gasket seal, the tube may be bolted securely to a base plate and its interior evacuated. Vacuum-tight thermocouple connections are provided in the base plate.

Preliminary experiments indicated that annealing at a temperature of approximately 1000 C in a pure nitrogen atmosphere at normal pressure to suppress sublimation would remove strain. Equally effective results were later obtained at a temperature of 800 C. The minimizing of temperature gradients in the furnace is the essential requirement. At 800 C it was possible to anneal the crystals in vacuum.

Crystals to be annealed are placed in heavy-walled graphite crucibles in the chamber of the furnace. Eight 2-in. diameter crystals or two 4-in. crystals can be annealed in one loading. A representative schedule for the annealing of a 4-in. crystal is as follows:

Heating to top temperature (750 to 800 C)	= 3.25	hr
Time at top temperature	= 9	hr
Automatically controlled cooling to 75 C	= 35	hr

At the latter point the power is zero. The furnace then was allowed to cool to room temperature (about 24 hr), the vacuum was broken, and the crystal removed.

For a 2-in. diameter crystal, the controlled cooling time was about 15 hr instead of 35.

Several crystals were satisfactorily annealed under conditions varying but slightly from those described while others showed bad strain even after treatment as nearly identical as possible. Schedules involving longer times of cooling removed most of the strain from these crystals but cracks developed during subsequent handling or processing, although all operations were performed cautiously. One may infer that the crystals having locked strains cannot be annealed satisfactorily by the standard method developed. It is evident that more study of the annealing process is required to insure uniformity of product.

The annealing furnace, as designed, was not strong enough to withstand evacuation at high temperatures. Air leaks through the welded seams appeared after short operation, followed by collapse of the stainless steel lining. A redesign of the furnace is indicated. Because of this failure, most of the annealing was done in the crystallizing furnace. The resulting crystals while not perfectly strain-free were sufficiently so for most optical purposes. They could be sawed, ground, and polished with reasonable care in handling.

SUMMARY OF CRYSTALLIZATIONS

The results of crystallizations in the various types of furnaces are presented in Table 3. The table includes the majority of crystals grown during the most vigorous prosecution of the work but does not include results of runs made for determining suitable furnace design, proper operating conditions, or quality of raw material.

The scarcity of large single crystals grown

in no way detracts from the importance of the development from the optical standpoint. Multiple crystals, with proper care, have been worked into lenses and prisms, and the multiple structure appears to have no appreciable deleterious effects on the quality of the optical part.

a spectrometer table at controlled air temperatures near 15, 35, and 55 C by the method of minimum deviation. The measures were then corrected to refer to air at the temperatures listed and at a pressure of 760 mm of mercury. The probable errors are estimated as not in excess of 2×10^{-6}, with systematic errors probably not in excess of two or three times the probable error.

TABLE 3. Results of crystallizations.

Type of furnace	Element diameter (in.)	Elements grown	Single clear	Multiple clear	Crystals annealed	Crystals grown with scavenger	Crystals with no scattering
Elevator type with molybdenum wound	1½	105	2	6	11	0	4
Alundum core	1	3	0	0	0	0	0
heater	1¾	15	0	0	2	0	0
	2	31	0	7	0	0	0
		154	2	13	13	0	4
Elevator type with	1½	124	23	37	32	73	43
graphite spiral	2	214	48	93	154	207	87
heater	1¾	1	0	1	0	0	0
	¾	324	59	143	14	23	52
	4	52	2	37	22	52	37
		715	132	311	222	355	219
Elevator type with vertical bar type heater	1	11	4	5	0	11	7
Pot furnaces	2	15	0	0	0	0	0
	1¾	12	0	8	0	12	0
	3¾	216	2	185	85	215	137
	6	16	0	15	4	16	11
		259	2	208	89	243	148
Grand totals		1,139	140	537	324	609	378

7.3 OPTICAL PROPERTIES OF SYNTHETIC FLUORITE CRYSTALS

REFRACTIVE INDEX

Two fluorite crystals were made into 60-degree prisms and transmitted to the Bureau of Standards for refractive index measurement.[5] The first of these, I-224, was figured by the Bausch and Lomb Optical Company from a crystal grown with scavenger from colorless New Mexico stock which had been processed once previously through the furnace. It had faces 40 mm on a side. The second prism, IX-7, with faces 75 mm on a side, was figured by the Perkin-Elmer Corporation. It was grown from Butler Cave fluorspar with scavenger.

The refractive indices of these 60-degree prisms were measured in a stirred air bath on

Table 4 exhibits the refractive indices averaged for the two prisms. The results for the 40-mm prism were, on the average, 5×10^{-6} higher than the values given in Table 4, and the indices for the 75-mm prism were correspondingly lower. These values average 13×10^{-6} higher than the indices of fluorite as measured by Schönrock at the Reichsanstalt and 6×10^{-6} higher than some measurements of natural CaF_2 made at the Bureau of Standards.[5]

From these data we find a ν-value of 95.2 at 15 C, and an average temperature coefficient of refractive index of -11×10^{-6} per degree centigrade.

The influence on refractive index of impurities in the synthetic CaF_2 crystals is insignifi-

[redacted]

cant. Measurement of n_D in a prism made from a crystal grown without lead fluorite scavenger yielded a value 1.43389 at 15 C, which is essentially the same as that recorded in Table 4 for crystals grown with the scavenger.

Transmission

Over the entire wavelength range from 0.4 μ to 6 μ the transmission of the artificial fluorite crystals, uncorrected for surface reflections, is nearly uniform at 93 per cent for a path of 31 mm. Figure 11 shows the transmission of one sample as a function of wavelength for this path length. It should be noted that in the range of wavelength less than 1 μ the scale of abscissae has been considerably expanded. The curve is compiled from measures made on a prism in the range from 0.4 μ to 10 μ. For the range below 0.4 μ, the measures were made with a vacuum grating spectrograph on various sample plates of CaF_2 and the results must be considered provisional.

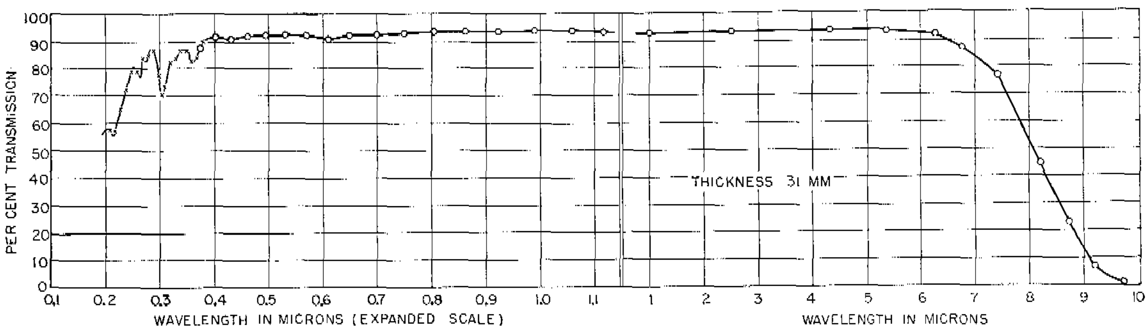


FIGURE 11. Transmission of artificial fluorite.

TABLE 4. Refractive index of synthetic CaF_2 crystals.

Wavelength (A)	Indices of Refraction 15 C	35 C	55 C
*7678.58	1.430984	1.430768	1.430546
7065.188	1.431763	1.431553	1.431331
6678.149	1.432356	1.432142	1.431922
6562.793	1.432545	1.432335	1.432114
*5892.62	1.433893	1.433683	1.433465
5460.740	1.435023	1.434813	1.434593
4861.327	1.437106	1.436894	1.436680
4358.342	1.439555	1.439354	1.439143
4046.563	1.441573	1.441378	1.441168

* Intensity-weighted mean of doublet.

The ultraviolet cutoff point of the material has been estimated from samples of crystal varying in thickness from 2 to 10 mm by examining the spectrum of an iron arc with the vacuum spectrograph. The mean of seven estimates is 0.132 μ ± 0.002. The cutoff point for a plate of natural fluorite 1.9 mm thick has been given as 0.124 μ.[6]

Homogeneity

The optical quality of five large fluorite crystals as regards homogeneity was measured in a preliminary way at the Mount Wilson Observatory and more completely at the National Bureau of Standards. The report of the National Bureau of Standards[7] will be cited in some detail, since it furnishes the most extensive and quantitative data.

Photographs of the fringe patterns produced in the Michelson-Twyman interferometer were made in unpolarized and in polarized light. The fringes, in general, appeared somewhat blurred because of double refraction. Because of relatively large deviations from homogeneity in the crystals it was not deemed necessary to photograph the fringes showing surface irregularities. Instead, careful drawings were made of these fringes and in determining the magnitude of heterogeneities within the cylinders, allowance was made for the deviations of the surfaces from true planes.

For purposes of comparison, a series of photographs was also made of a specimen of natural fluorite which was available in the form of a 60-degree prism. The natural fluorite used was not entirely free from visible defects and does not represent the best quality that is some-

[redacted]

times available. The prism, however, has served satisfactorily for research work.

The five cylinders of synthetic CaF_2 crystals were 100 mm in diameter and varied in thickness from 38 to 51 mm.

The variation in optical path length from an assumed normal value through each specimen was measured, allowance having been made for irregularities of both surfaces of the crystal. Maximum path-length differences, expressed in wavelengths of green light over a central portion of the crystal 75 mm in diameter, were found to be: 1.4, 0.8, 0.8, 0.6, 1.0 for crystals numbered 1 to 5 respectively. These values are for a single path through the crystal and arise from heterogeneities within the material. For a path length of 2 in. in optical glass of the same aperture, one would not expect path differences due to inhomogeneity to exceed 0.05 wavelength.

Figures 12 and 13 show the fringe patterns for specimens No. 3 and 5, both in polarized and in unpolarized light. The abrupt curvature of the fringes at the edges of the crystal is caused by dubbing of the surface ends. The streaks on the third vertical fringe and across the two vertical fringes at the right side of specimen No. 3 are probably caused by twinning of the crystals. The whorled effect in No. 3 resembles the markings caused by striae in glass. In specimen No. 5 there is a cleavage plane horizontally across three vertical fringes on the right. The smaller streaks, white spots, and apparent sharp displacement of fringes in this specimen are caused by scratches and marks on the surface.

It is evident that the fringe patterns in polarized light are much sharpened. The photographs taken with polarizer and analyzer crossed reveal considerable stress in the crystals. The birefringence was not measured quantitatively but appears to be considerably more than is tolerated in optical glass. For the latter the tolerance is 10 mμ per cm although most of the optical glass now produced shows a birefringence no greater than 5 mμ per cm. In specimen No. 3 the crystal multiplicity shows plainly.

Figure 14 shows the interference pattern photographed through a 60-degree prism of natural fluorite, the maximum path length being 51 mm. The variation in sharpness and regularity of fringes from one side to the other arises from the variation in path length through the prism and does not indicate any regular variation in quality of the specimen. Opaque spots in photographs made with the unpolarized light are apparently due to small facets or fractures in the interior of the crystal which have an iridescent appearance. In polarized light the pattern is mottled and much finer grained than is the pattern for the synthetic crystals. Presumably a finer grained stress pattern is indicated.

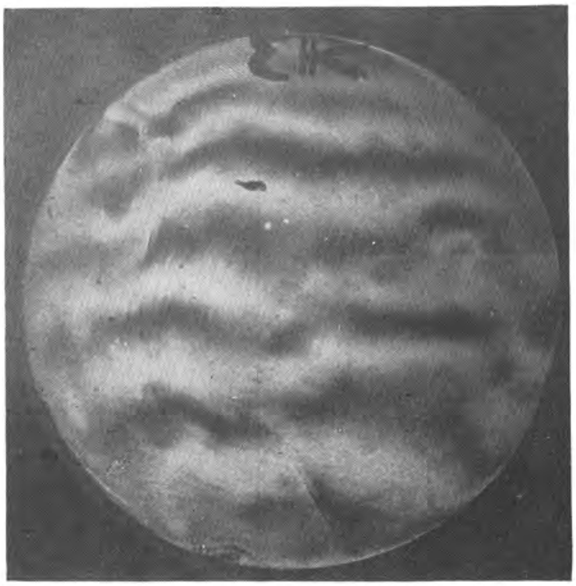
7.4 OPTICAL WORKING OF SYNTHETIC CRYSTALS

No matter how completely internal stresses have been removed from the fluorite crystal by annealing, a thermal shock will introduce a certain amount of stress temporarily. Sudden changes of temperature, such as would occur if the crystal were submerged in cool water after optical working, must be avoided.

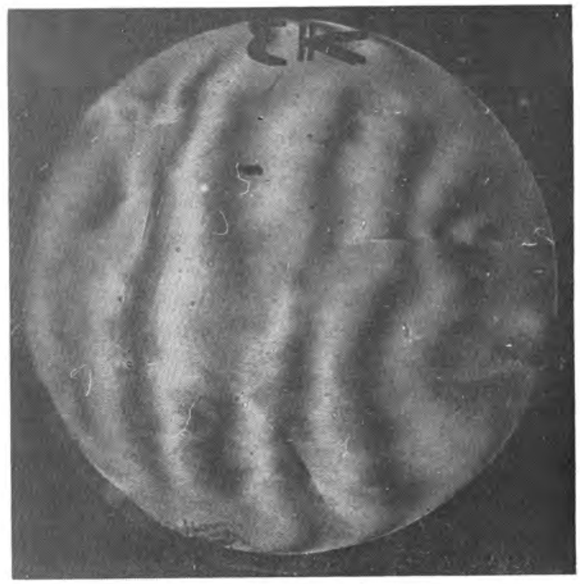
Cutting of crystals may be carried out with a diamond saw with proper precautions. If the crystal is washed in water which is 5 C cooler than the crystal, the latter will almost certainly crack. As a test to determine whether thermal shock alone is sufficient to cause shattering, a stream of cold tap water was allowed to fall on an annealed 3¾-in. multiple crystal. It was shattered immediately. Furthermore one of the pieces which was crystallographically single quickly broke when it was placed in the cold-water stream.

This result has been borne out by the experience of optical workers who have been developing methods of grinding and polishing fluorite surfaces. Thermal shock has been found to be far more serious than mechanical shock. Size of disk has a great deal to do with resistance to thermal shock. No 2-in. disks were broken in experiments on grinding and polishing, but some thick 4-in. disks broke in spite of care.

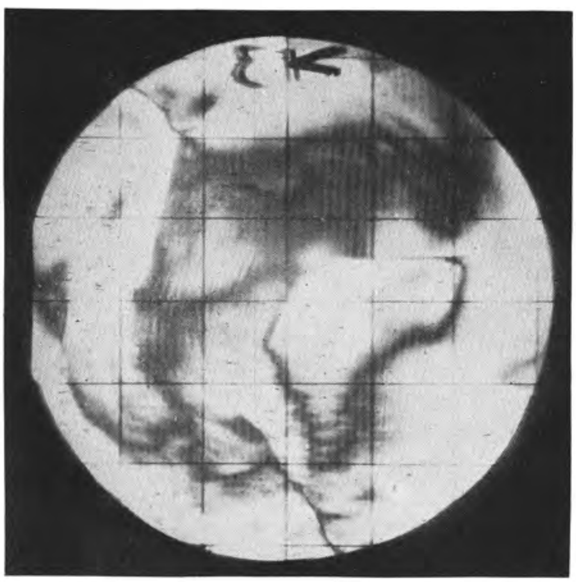
It is evident, therefore, that the crystal must be kept at room temperature as nearly as pos-



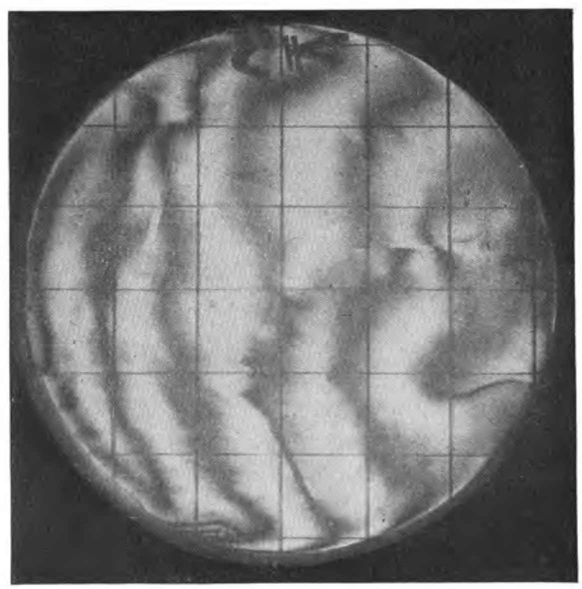
LIGHT UNPOLARIZED
FRINGES HORIZONTAL



LIGHT UNPOLARIZED
FRINGES VERTICAL



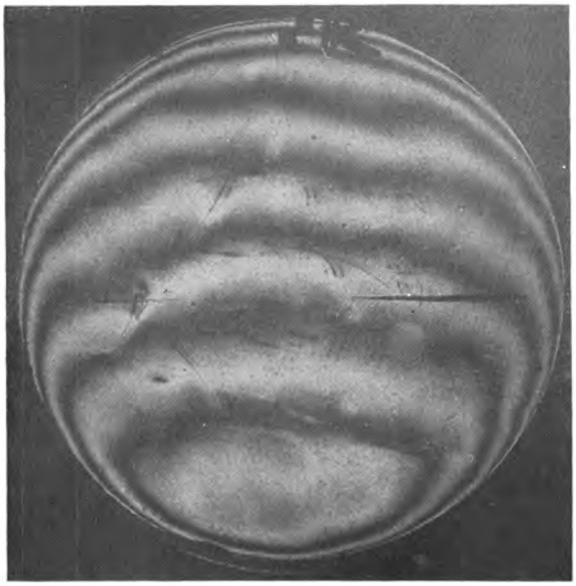
LIGHT POLARIZED
POLARIZER AND ANALYZER PARALLEL
FRINGES VERTICAL



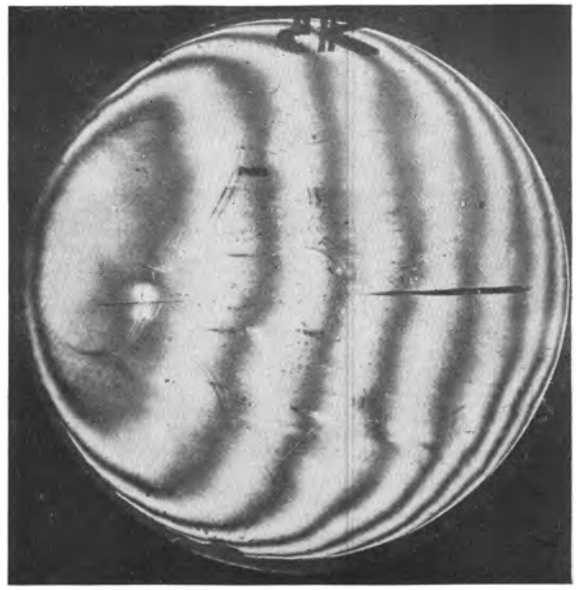
LIGHT POLARIZED
POLARIZER AND ANALYZER PERPENDICULAR
FRINGES VERTICAL

FIGURE 12. Interference pattern—artificial fluorite, specimen No. 3.

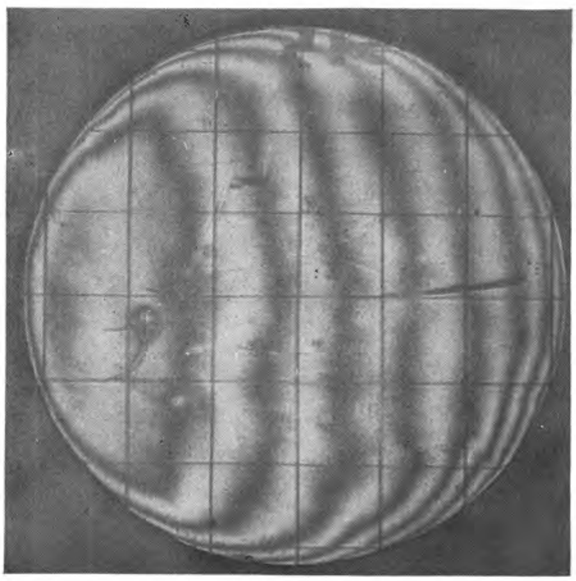
[redacted]



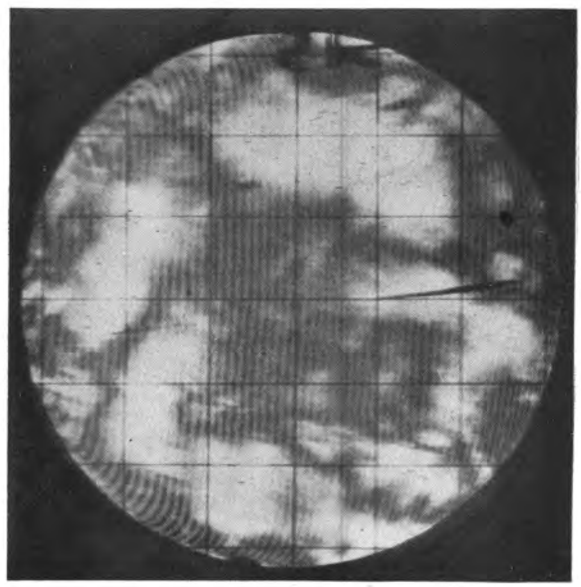
LIGHT UNPOLARIZED
FRINGES HORIZONTAL



LIGHT UNPOLARIZED
FRINGES VERTICAL



LIGHT POLARIZED
POLARIZER AND ANALYZER PARALLEL
FRINGES VERTICAL



LIGHT POLARIZED
POLARIZER AND ANALYZER PERPENDICULAR
FRINGES VERTICAL

FIGURE 13. Interference pattern—artificial fluorite, specimen No. 5.

[redacted]

sible during optical working. It must be worked slowly and allowed to stand after working and before washing. The water in which it is washed must also be at room temperature.

This sensitivity to thermal shock is not uniquely characteristic of synthetic fluorite. It has been demonstrated repeatedly that natural fluorite crystals crack when treated similarly.

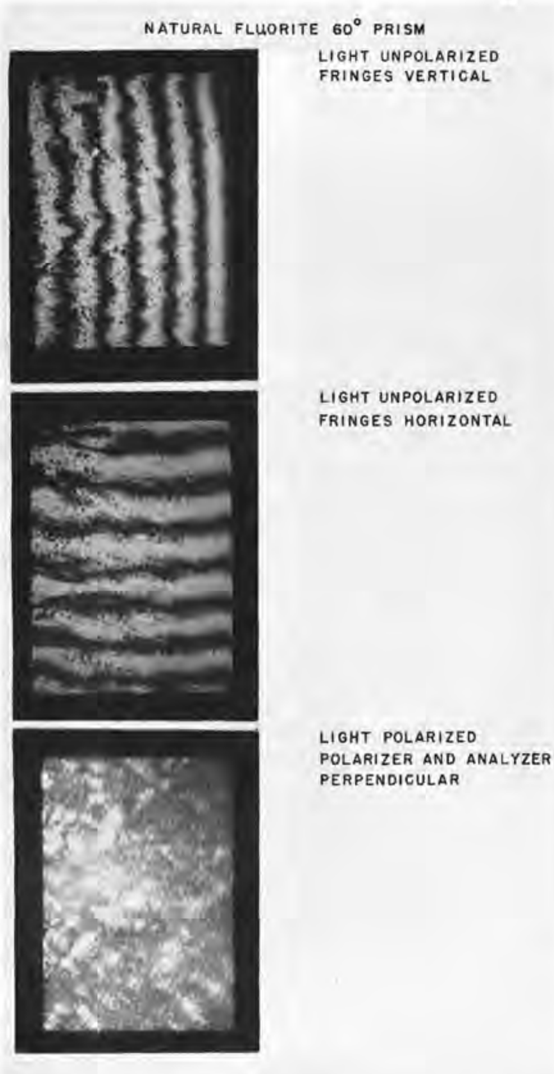


FIGURE 14. Interference pattern—natural fluorite.

Techniques for figuring fluorite surfaces have been worked out by the Perkin-Elmer Corporation, under Contract OEMsr-1177, and by Harvard under Contract OEMsr-474. The general conclusions of the former may be summarized as follows:

1. In the rough grinding stage mechanical shock is likely to arise if the roughing is done with coarser than No. 120 Carborundum. No. 240 Carborundum or emery is recommended as a start; coarser grades cause chipping, flaking, and subsurface fracturing.

2. In spite of all care in the polishing stage, the soft crystalline materials show a tendency to flake. These flakes are a source of sleeks and scratches. The elimination of difficulty from this source constitutes the major problem in working the synthetic crystals.

3. It is advantageous to produce as fine a ground surface as possible before polishing. Very long polishing times are required, at best, to remove the subsurface fracturing caused by the grinding materials. The fractures appear to extend to a depth several times the size of the grains used in grinding. In the polishing process the crystal layers present a "grain" appearance not met in the polishing of homogeneous material like glass.

4. The presence of a scratch interferes with figuring, presumably on account of the internal stress in the fluorite. The test plate shows a figure error amounting to several waves surrounding such a scratch and the error remains until the scratch is completely eliminated. The area affected depends on the depth of the scratch, extending sometimes as far as $\frac{1}{4}$ in. from the scratch.

5. In samples figured from multiple crystals, it was found that on a face showing parts of several crystalline components, each of the parts persisted in standing at a different level (approximately a quarter-wave) from its neighbors. Each component part of the crystal, nevertheless, was flat to a tenth of a wave without rolled edges at the crystal boundaries.

6. The reaction products arising from the polishing of fluorite appear to produce a glaze over the lap which interferes with polishing. This is in sharp contrast to the polishing of glass with a pitch lap, where the reaction products actually assist in the operation.

These general conclusions are confirmed by the experience at Harvard in the grinding and polishing of fluorite. It was found there that

[redacted]

when emery replaced silicon carbide as the principal grinding agent many of the fractures and cracks resulting from the latter did not appear. Bonded diamond wheels were used to generate the required curves and emery was used for the final grinding with very satisfactory results.

After considerable experimentation, a technique suitable for working these crystalline surfaces was developed by Perkin-Elmer. The experience was gained by working (1) two CaF_2 prisms of 60-degree angle, (2) five CaF_2 disks 4 in. in diameter and 2 in. thick, (3) two small 60-degree prisms, one of BaF_2 and one of SrF_2, (4) twenty-four disks of CaF_2 about 50 mm in diameter and 12 mm thick, and (5) many small pieces for experimental purposes only.

The technique recommended[8] for the surface working of these crystals follows:

1. *Blocking.* Since fluorite cannot stand the heat of regular blocking pitch, a soft, nonflowing, adhesive wax was necessary for attaching hubs to the work. A very satisfactory composition for the purpose is:

Rosin	200	parts
Asphalt	150	"
Beeswax	100	"
Paraffin	25	"
Rouge	200	"

The hub is heated and smeared with a little of the wax. When this has cooled, it is exposed very briefly to a flame and then pressed against the fluorite. It takes very little heat to bring this wax to a point where it will adhere firmly. The hub is removed afterward with a light tap.

Unless the pieces are small (1 in. or less in diameter), it does not seem worth while to block them in groups for polishing. The ease with which the material is scratched means that a high percentage of reworks would result from each plateful. The optical figure, furthermore, cannot be corrected when several pieces are blocked at once, since each piece acquires a rolled edge. Multiple blocking is, however, a timesaver in the grinding stages.

2. *Grinding.* For rough grinding, No. 240 Carborundum or emery wet with water is used; coarser grades cause too much chipping, flaking, and subsurface fracturing, although they are unlikely to cause breakage. For fine grinding, the succession is No. 3F, No. 900, No. 1600, and (if the operator can manage it successfully) No. 2600, all of these being wet with denatured alcohol or a large amount of water. Sodium oleate solution and ethylene glycol were tried as substitutes for alcohol, but were not so satisfactory. In working with alcohol, the fluorite should be taken off the lap at each wet, and run in a little by hand after the alcohol and emery are added. After three or four wets, the fluorite and the tool should be wiped clean before proceeding, in order to avoid scratches. To use extreme care, the operator should do his wiping after every wet. He may avoid the necessity of running in by hand if the iron tool has approximately double the diameter of the work. With a slight amount of overhang in the stroke, there is then no part of the tool which is always against the fluorite. The abrasive can be introduced at the center of the tool and caused to spread evenly by the motions of the machine.

3. *Polishing.* Both on cloth and pitch laps, it was found that rouge, cerium oxide, or Barnesite produced many scratches and sleeks. More success was had with Linde A and Linde B, which are finely divided sapphire, the particles in the former being less than 0.3 μ in diameter and in the latter less than 0.1 μ. These materials work faster and cleaner when wet with saturated salt solution instead of water. The technique followed involves (1) running the work rapidly on a cloth lap with Linde A, and (2) on a soft pitch lap (Burgundy) with Linde B at a moderate running speed (150 rpm). To remove the sleeks formed in this step, the operator then (3) goes back to a cloth lap and Linde A. A minimum of pressure is used in these steps, i.e., the weight of the work and the stroke arm. Since figuring must be done on pitch, it will be seen that the conditions of good figure and freedom from sleeks are very difficult to obtain simultaneously. When glass-working methods are applied to fluorite, the result is a maze of fine scratches. The surface looks like a piece of glass which has been polished on a lap very badly contaminated with grit.

The pitch lap is made of Zopharlac, and the cloth lap of standard white polishing cloth such as manufacturers of spectacle lenses use.

4. *Edging.* Disks may be edged on a horizontal spindle with loose grit and a strip of brass.

7.5 OTHER ARTIFICIAL CRYSTALS

During the latter part of the experimental phase of the work under Contract OEMsr-45, crystals of barium fluoride and strontium fluoride were grown. The technique followed was very closely the same as for CaF_2. Measurements of the refractive index were made at the National Bureau of Standards on 60-degree prisms made from 2-in. cylinders of BaF_2 and SrF_2. The data obtained are shown in Table 5.

TABLE 5. Refractive index of BaF_2 and SrF_2.

Wavelength (A)	SrF_2 15 C	SrF_2 35 C	SrF_2 55 C	BaF_2 15 C	BaF_2 35 C	BaF_2 55 C
*7678.58	1.435136	1.434898	1.434652	1.470533	1.470233	1.469925
7065.188	1.435916	1.435672	1.435431	1.471469	1.471167	1.470869
6678.149	1.436508	1.436268	1.436031	1.472199	1.471892	1.471591
6562.793	1.436703	1.436470	1.436226	1.472444	1.472130	1.471835
*5892.62	1.438082	1.437848	1.437606	1.474127	1.473815	1.473520
5460.740	1.439245	1.439008	1.438771	1.475561	1.475255	1.474951
4861.327	1.441402	1.441172	1.440932	1.478237	1.477926	1.477634
4358.342	1.443964	1.443742	1.443505	1.481421	1.481112	1.480819
4046.563	1.446085	1.445857	1.445632	1.484054	1.483753	1.483468

* Intensity-weighted means of doublets.

These refractive indices were measured[9] in a stirred air bath on a spectrometer table at controlled air temperatures near 15, 35, and 55 C by the method of minimum deviation. The probable errors are estimated to be not over $\pm 2 \times 10^{-6}$; systematic errors probably do not exceed two or three times the probable error.

The surfaces of these prisms were not as flat as might be desired and it was found necessary to diaphragm the prisms in order to exclude the especially defective areas within 3 or 4 mm of the edges. The remaining apertures were used symmetrically during all measurements.

The transmission characteristics for these materials have not been accurately determined at present. The barium fluoride sample shows considerable absorption, as is evident by visual inspection of the crystal. Other crystals, however, give a visual impression of being highly transparent, and so it will be extremely desirable to measure the transmission of additional samples. The cutoff wavelength for a BaF_2 crystal 2-mm thick was estimated at 0.139 μ, while that for a crystal of SrF_2 was 0.125 μ.

7.6 PRESENT STATUS OF DEVELOPMENT OF ARTIFICIAL FLUORITE

Artificial CaF_2 crystals, grown from the melt as described in the preceding pages, have been found quite satisfactory for lenses in highly critical instruments such as aerial cameras. Multiplicity of the crystal does not appear to be seriously objectionable in lens applications. The principal disadvantage lies in the extreme fragility of the material. If the fluorite lens component is cemented between glass elements its fragility is somewhat overcome and at the same time the tolerance on surface accuracy may be relaxed. Soft cement is used for the purpose in order not to set up objectionable stresses. The lenses (two of them), made with a CaF_2 component placed between appropriate glasses, were almost completely color free. The other aberrations were small and after proper design apparently were in no way enhanced by the fluorite component. Details of these lens systems are given in Chapter 1.

Undoubtedly a considerable amount of de-

[redacted]

velopment in manufacturing methods will be required to place the production of these crystals on a commercial basis. Studies of power rates and elevator rates as a function of crystal size must be continued in order to insure a high yield of good quality crystals. Annealing studies and the design of a new furnace for this treatment are clearly indicated.

For infrared spectroscopy, the prisms obtained from 4-in. CaF_2 cylindrical crystals are in great demand. Lithium fluoride prisms, now used for this work, usually have an objectionable absorption band due to HF, which the fluorite does not possess.

At the conclusion of the research described, the principal defect observable in the synthetic CaF_2 crystals appeared to be the lack of homogeneity due to stress in the material. If annealing methods can be developed to the point where a high percentage of the crystals can be relieved of this fault, the successful use of CaF_2 components in optical systems of some size for removal of secondary spectrum seems assured.

The stockpile of crystals produced at the Crystallographic Laboratory of MIT under Contract OEMsr-45 has been transferred to the National Bureau of Standards. These crystals will be available for use by government laboratories and, under certain circumstances, for noncommercial experimental use in private laboratories.

7.7 OPTICAL APPLICATIONS OF FLUORITE

The success attained in producing large disks of synthetic fluorite carried with it the possibility that the resolution of aerial lenses might be improved by its use. In 1942, information as to what factor most seriously limits resolution in the air was very meager. It was considered reasonable that the color errors known to be present in all standard lenses might very well be one of the serious barriers to better results. For this reason Harvard was requested to accept a contract, OEMsr-474, for the purpose of initiating and developing the use of synthetic fluorite in an aerial camera lens.

From the early days of the German optical industry natural fluorite has been used in apochromatic or semi-apochromatic microscope objectives. No one in practice considered fluorite for other purposes, owing to the drastic limitation on available diameters and to the great monetary value attached to even small pieces.

The use of fluorite in combination with quartz for apochromatic doublets, particularly for ultraviolet work, is well known. Equally well known is the fact that fluorite combines well with crown glass for visual objectives essentially free of secondary spectrum.

Reference to the comments on secondary spectrum in Section 1.2.1 will reaffirm that only for long spectral ranges, as in color photography, or for large lens diameters, will secondary spectrum constitute a serious limitation to the quality of aerial photography. Indeed, yellow and red resolution tests of the 100-in., $f/10$ lens (Figure 76 of Chapter 1) show little difference, in spite of the design correction at 6250 A and visually observed aberration in yellow and green. In 1942 the point of view was less clear-cut, but it was realized that fluorite should be used for the larger lenses. A Harvard report notes that it was a standing request to the project on fluorite at MIT to produce as large a disk as possible.

The development of camera lenses employing fluorite has already been discussed in Section 1.3 in connection with aerial equipment. At this point it would seem expedient to add a few summarizing general remarks likely to aid further work along these lines.

The index of refraction of fluorite is much too low for general utility in the design of aerial lenses, being only 1.43385 for the D line. In combination with achromatizing elements of crown glass, the situation is slightly improved by the co-existence of a very high ν-value, 95.4, which in turn tends to result in weaker internal curvatures. In practice, the curves are made as strong as correction of the aberrations so introduced will stand. It would appear that, even with prolonged designing, speeds which are greatly in excess of $f/8$ over the large angular fields now known to be imperative are un-

attainable with fluorite apochromatic systems.

The secondary spectrum characteristics and the high ν-value of fluorite demand that fluorite be used solely for positive elements, if an apochromatic correction is desired. Great damage is imparted to the Petzval sum, which cannot be overcome in many familiar types of all-glass lens designs altered for the use of fluorite.

In the 36-in. apochromatic lens which employs fluorite, the Petzval sum was made sufficiently low in spite of the use of fluorite, by means of a long lens barrel. The resulting higher order astigmatism constituted the limiting aberration in the corners of the 9x9 picture. It might be possible to obtain a larger coverage, but the design would no doubt become very complex.

The device of lengthening the lens barrel for obtaining shallow curves in spite of the low Petzval sum required is expedient only for small angular coverages. The disadvantage of fluorite to the Petzval sum would have been far more marked had not the design made good use of the material in the form of an elaborated Cooke triplet which contained a cemented triplet for the negative control component. In the Cooke form, one usually gains considerable net power for a given barrel length.

Two additional effects helped the success of the Harvard design. The use of the fluorite at a low relative height in the lens system diminished its effect on the Petzval sum. Moreover, much of the achromatizing of the outer positive elements was accomplished by means of negative glass elements of the same or similar glass type. Thus, the fluorite had only to overcome the difference, amounting probably to about half of the required overall correction. Finally, the curvatures required at the low relative height were in the most symmetrical position within the Cooke triplet form, and behaved with good consistency over the entire required field.

The chief defect remaining in the final lens design is higher order astigmatism in the corners of a 9x9 picture, produced by the large air space between the first and second elements. At large oblique angles, the tangential focus is pulled forward, before the middle elements have had a chance to compensate. This distance effect becomes very pronounced in the corners of the picture, even to the extent that the variation of astigmatism with color becomes noticeable. On the other hand, the design chosen minimizes the overall aberrations, and within the included circle of a 9x9 picture gives optimum resolution.

Almost the sole advantage of fluorite is the elimination of secondary spectrum. Its use introduces abnormally large monochromatic aberrations and errors in spherical chromatism which present a real difficulty for the designer to overcome. In an apochromatic system it is of no use to replace the normal color blur by a monochromatic blur of the same image cross section. Consequently, the fluorite apochromat requires the designer to obtain unusual quality, in spite of unusual obstacles. Obviously, a material of high index and high ν-value, accompanied by suitable secondary spectrum characteristics, would produce a drastic improvement in apochromatic aerial lenses in speed, angular coverage, and resolution.

Fluorite is a relatively insoluble crystal. It is mechanically weak and has a thermal expansion coefficient of 19×10^{-6} per degree centigrade, double that of ordinary optical glass. Consequently, large diameter elements of fluorite cannot be cemented tightly to glass mates. The Harvard lenses made use of plasticized Transil Oil with success, even at extremely low temperatures. Fluorite lens elements are almost always biconvex and steeply curved. The accompanying thin edge is stretched around a thick center. Any sudden cooling will almost inevitably start a crack in the lens. Ordinary handling by the optician is hazardous.

Fluorite has also a great change of index of refraction with temperature, amounting to -0.00001 per degree centigrade rise in temperature. The ensuing change in focus of a large apochromatic lens is many times the tolerable depth of focus. It is therefore imperative that aerial lenses making use of fluorite be thermostated.

Along with the application of synthetic fluorite to aerial lenses, Harvard (Contract OEMsr-474) completed several other types of apochromatic instruments.

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7.7.1 1.8-in., f/20 Apochromatic Triplet Fluorite Objective

The first completed optical instrument employing synthetic fluorite was a cemented triplet telescope objective, 1.8 in. in diameter. The design was corrected for both spherical aberration and coma, in addition to a very thorough color correction. The system made use of negative elements of C-1 glass enclosing the single positive element of fluorite. The internal cemented surfaces represent such a drop of index and such relatively steep curves that full correction is possible for both coma and spherical aberration.

Tests made with this objective confirmed the almost complete absence of color. According to design figures, when F and C (wavelengths 4,861 and 6,563 respectively) are combined, the discrepancy in focus at 5,500 A amounts to only 0.000170, still of the nature of ordinary secondary spectrum. It is stated that only uncertainty in glass indices prevents the residual from being zero. Even so, the secondary spectrum has been reduced to very closely one-third of the normal glass value, and at $f/20$ has brought a very long spectral range within the Rayleigh limit.

7.7.2 6-in. Dialytique Apochromat Objective

In November 1942, disks of fluorite as large as 3¾ in. in diameter were available in advance of a completed design for an aerial camera. In order to ascertain the probable performance of fluorite with large aperture and lenses of long focal length, it was proposed under the Harvard contract to construct a 6-in. aperture apochromatic telescope, in which the apochromatic color correction is achieved by means of a hyperchromatic combination in the converging beam of the telescope. Figure 15 shows a cross section of the test instrument.

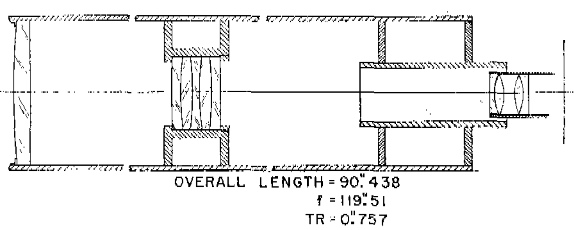

FIGURE 15. The 6-in. aperture, $f/20$ dialytique apochromat.

The performance tests were conclusive. It was found by autocollimation that the resolving power obtained agreed closely with theoretical requirements, and that the scattered light found around the image was very slight. These results were obtained in spite of the fact that tests through crossed Polaroids showed the presence of considerable strain in the two fluorite disks used in the design.

The telescope has never been completed, although a mounting was finished to hold all lens elements securely in line for testing purposes. It should be noted that such a color-corrected instrument will have considerable lateral color which must be eliminated by means of a special eyepiece design. Figure 16 reproduces the color curve of the ordinary glass achromat and the calculated curve of the dialytique apochromat.

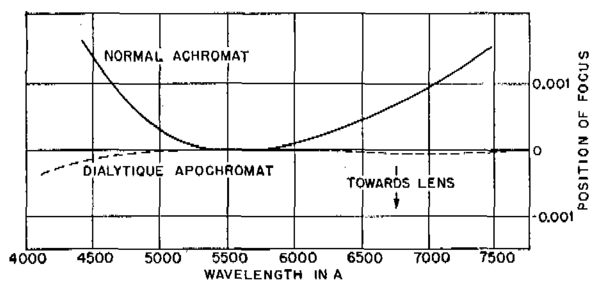

FIGURE 16. Color curve of dialytique apochromat.

7.7.3 A Folded Apochromatic Telescope and Collimator

Figure 17 shows a larger diameter objective made in accordance with the specifications of the cemented triplet form of objective. The focal length is 70 in. and the clear aperture 3.5 in. The complete length of the folded system amounts to only 30 in. and the weight to 20 lb.

The eyepiece shown in the drawing can be replaced by either a draw tube with light source of any description for use as a collimator, or by a Leica camera attachment for use as an analyzing telescope.

Reference to Figure 17 will show that light trapping for outdoor use is not sufficient. There is direct illumination falling on a considerable length of the eyepiece drawtube. In daytime application, to which it seems best suited for military purposes, it will be necessary to add additional stops and to adopt a fiber-black in-

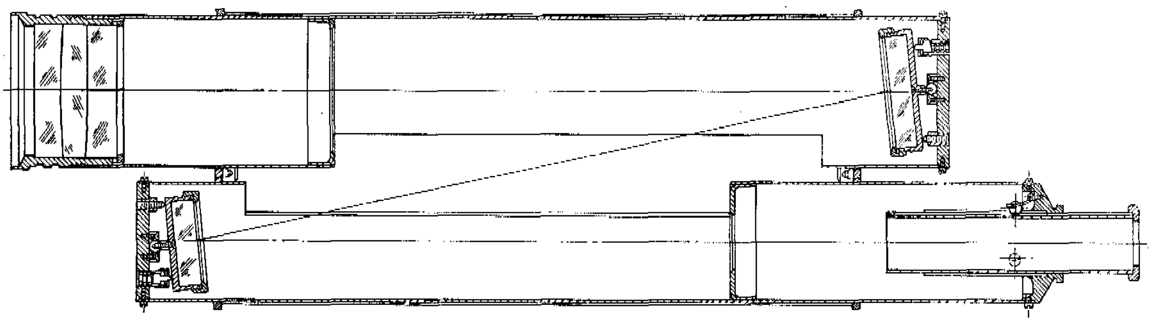

FIGURE 17. Folded fluorite apochromat telescope.

ternal coating, at least in the drawtube. A sufficient gain in light trapping might be made by shortening or inverting the drawtube arrangement.

The specifications of the $f/20$ objective are shown in Table 6.

TABLE 6. Optical data of an apochromatic triplet.

Surface	Radius (in.)	Thickness (in.)	Glass type
1	33.22	0.772	C-2
2	20.14	0.772	fluorite
3	—25.59	0.772	C-1
4	—83.52	...	...

It is of interest to give more data for this system, inasmuch as the computations were carried to nearly an ideal level. The indices as used are shown in Table 7.

TABLE 7. Indices of materials for apochromatic triplet.

n_C	n_D	n_F	Glass type
1.50952	1.51200	1.51798	C-2
1.43250	1.43385	1.43706	fluorite
1.51993	1.52260	1.52883	C-1

Thick lens elements are used in order to overcome any possible flexure caused by cement. The system as given is designed for optimum performance in e (5,461 A) light. Calculations show that the lens yields three coincident foci, based on aperture and diffraction considerations, that occur at 4,700, 5,500, and 7,000 A. The maximum deviation is less than 10 per cent of the normal achromat error, for which F and C are usually combined. Longitudinal Aberration:

Rim ray at $f/20$	(D — e)	—0.000007
Rim ray at $f/20$	(F — e)	—0.000053
Paraxial	(F — e)	—0.000081

The telescopic image was found to be excellent and quite free from visual color aberrations. At a power of 350× or 100× to the inch of aperture, only a slight trace of astigmatism was found. There proved to be no observable variation in quality over the field of 1 in. diameter permitted by the mounting.

This folded system seems to be thoroughly practical for a medium aperture apochromatic system of general utility. It is recommended that this form of telescope be considered by the Armed Forces as suitable for tripod mounting in the field, and that it be further modified for field work by installation of an inverting system. Even a brief examination of the colorless image will impress an observer who is accustomed to ordinary achromatic objectives.

7.7.4 Yerkes Apo-Periscope Objective for Mark IV Periscope

A more complete discussion of the optical characteristics of this objective is given in Chapter 10. The optical work was carried out

[redacted]

at Harvard. The fabrication of the four air-fluorite surfaces required several times as much careful work as in the case of the three glass lenses. The glass surfaces were worked with unusual care in order to place the burden of any residual errors on the fluorite elements. Every attempt was made to finish the fluorite lens elements to similar quality, but with no final success. They were marred by several small holes surrounding pits in the surface. Continued polishing produced new pits and new holes (see Section 7.4). The final objective produced a slightly hazy image, owing to light scattered from the four surfaces. It is believed that continued experimentation by a skilled optician trained in physical concepts would produce flawless fluorite surfaces.

7.8 ASSOCIATED MATERIALS

The primary purpose of the development of fluorite under NDRC was to provide a new optical material for the improvement of image quality in aerial camera lenses and other optical instruments. It is debatable in the light of war experience whether the effort devoted to the development of fluorite might not have been more valuable if used to produce materials of higher index. In defense of the work on synthetic fluorite it should be noted that its manufacture represents a technical triumph of considerable magnitude and that there undoubtedly will appear many uses of ultimate importance to science and to the country.

A number of optical materials other than fluorite were considered in connection with the design of aerial lenses. None of these reached the state of perfection acquired by fluorite, owing mostly, it is believed, to the lack of sufficient experimentation by qualified laboratories.

Table 8 lists a number of optical materials that merit notice. Although rare-earth glass represents one of the most important advances in glass technology in recent years, it was not an NDRC development. Its use is described below in connection with general comments on optical materials.

Spinel. Of the materials listed in Table 8, the most desirable from the point of view of optical design, although not from a practical standpoint, are spinel, for use as positive elements, and the alkaline halides, for use as negatives. Information at hand on spinel is too uncertain

TABLE 8. Optical constants of important materials.

Material	Index n_D	Reciprocal dispersion	Design utility	Practical utility
rare-earth glass*	1.745	45.7	excellent	excellent
spinel	1.723	64	excellent	doubtful
lithium fluoride	1.3915	83.3	poor	poor
lithium chloride	1.662	39.6	fair	poor
lithium bromide	1.784	28.4	poor	poor
lithium iodide	1.955	20.5	poor	poor
sodium fluoride	1.3258	83.5	poor	poor
sodium chloride	1.5441	42.8	good	poor
sodium bromide	1.6412	32.1	good	poor
sodium iodide	1.7745	22.0	good	poor
potassium fluoride	1.361	80.2	poor	poor
potassium chloride	1.490	44.0	good	poor
potassium bromide	1.5594	33.2	good	poor
potassium iodide	1.6670	23.3	good	poor
rubidium fluoride	1.398	81.2	poor	poor
rubidium chloride	1.4936	43.7	good	poor
rubidium bromide	1.5528	33.9	good	poor
rubidium iodide	1.6474	23.5	good	poor
caesium fluoride	1.478	75.9	poor	poor
caesium chloride	1.534	46.0	fair	poor
caesium bromide	1.582	34.2	good	poor
caesium iodide	1.661	23.5	good	poor
β-magnesia	1.738	53.5	good	poor
calcium fluoride	1.4338	95.4	poor	good
barium fluoride	1.4741	81.7	fair	good
strontium fluoride	1.4381	93.2	poor	good
cyclohexyl-methacrylate	1.5064	56.9	fair	good
styrene	1.5916	31.0	good	good
diamond	2.419	45	excellent	eventually

* There are a number of other types.

for any conclusion to be made as to its secondary spectrum characteristics. However, measurements on a poor sample indicate that spinel would combine well with the various flint glasses. Similarly, data on the characteristics of the halides are not at hand, but inspection, as well as computations based on patent literature, indicate that some reduction of secondary spectrum is obtainable in combinations of the halides with the barium crown glasses. Consequently, it is likely that combinations of spinel and the halides will lead to systems with improved color correction.

Spinel is a water-white crystal with a hardness equal to that of sapphire. Measurements made at Harvard indicate a ν-value of about 64 with a D-line index of 1.723. From a design point of view such optical properties are admirable. From a practical point of view, samples of spinel produced up to 1945 seem to have a considerable variation of index, amounting to about one unit in the third decimal place. Spinel would be very difficult to fabricate into lenses. From brief NDRC experience it would seem that it can be more easily polished with Linde A or B than with rouge or barnesite. As a front element for a military lens, once properly made, it would be nearly ideal because of its nearly complete mechanical and chemical resistance.

The Alkaline Halides. These materials can be grown synthetically and a few of those listed are available commercially. All the halides are water-soluble to some appreciable degree. However, freshly polished surfaces untouched by fingers or deleterious atmospheric gases will survive for a long time in ordinary indoor use if protected against dampness and circulated air.

The halides are unusual, compared to optical glasses, at least in part since many of them combine an unusually low ν-value with a fairly average index of refraction. Thus, potassium bromide has the ν-value of an extra dense flint glass, but the index of a light barium crown. Many photographic lens designs are in need of just such materials.

The halides offer many practical disadvantages. Polished surfaces do not resist abrasion, and, exposed to military use, would soon deteriorate beyond repair. Although it may prove possible to coat the surfaces with hard, nonreflecting films in spite of the obviously difficult cleaning problem, it would seem more practical from a military point of view to protect the halide elements by surrounding elements of glass, preferably cemented. Owing to a relatively high thermal expansion, the cement used would have to permit differential expansion without strain.

Magnesium Oxide. Magnesium oxide or β-magnesia has desirable optical properties, except that its secondary characteristics are in the wrong direction for a positive material. Apochromatic doublets of quartz and β-magnesia have been designed in which the MgO is used as the negative material. Practically, the material is available (as of 1945) only in small sizes. Polished surfaces are short-lived in a moist atmosphere.

The Fluorides. Calcium fluoride or fluorite has already been described in detail. Barium fluoride has been mentioned under Section 1.3 in the description of an apochromatic telephoto lens. Its optical properties are sufficiently superior to those of fluorite to warrant substitution in further apochromatic design work. Attention is drawn, however, to the need for further studies of the transparency of barium fluoride. The only existing data, although very uncertain, indicate that the transmission is too low for use in normal lens thicknesses. Before new design work is accomplished, the transmission curve of barium fluoride should be well established.

In addition to calcium fluoride and barium fluoride, measurements were made on strontium fluoride. The secondary spectrum characteristics proved to be intermediate between fluorite and barium fluoride. Strontium fluoride is therefore superior to fluorite, and would serve as a substitute for barium fluoride, should the latter be found inadequate in transparency.

Plastics. Any endeavor to design a fully corrected photographic lens of normal field angle, making use of only cyclohexylmethacrylate [CHM] and styrene, is fraught with many difficulties. The two materials are essentially an old style pair and for many applications are in violent conflict with the requirement of the Petzval sum. It is possible to overcome the objection by employing designs with large lens thicknesses, field flatteners, and perhaps aspheric surfaces. But whatever is possible along these lines with plastic is less difficult with optical glasses, which in turn would lead to better glass lens designs. In general, the designer's work is materially increased when only plastics are used.

Viewed in combination with glass types it is quite possible that plastic lenses have more to offer. Styrene is exceptionally valuable as a

[redacted]

negative material because of the low ν-value for its index. In many applications styrene will excel any available glass. The several alkaline halides with similar optical properties are inferior to styrene from a practical point of view. Styrene has a large dependence on temperature, relative to change of index and volume expansion. Because of the unusual dielectric strength of styrene, any unprotected surface of styrene soon collects large quantities of dust and lint. A coating of a slightly conducting material will remove this difficulty.

Cyclohexylmethacrylate has unusually good secondary spectrum characteristics to the extent that combined with medium flint glass secondary spectrum in the visual range is almost completely removed. For systems where plastic optics are applicable, this favorable color correction ought not be overlooked. It would be possible to design an aplanatic, nearly apochromatic, cemented triplet of CHM and DF-2 that would serve well for low power instruments covering a long spectral range.

In the preceding comments it will be understood that the range of requirements of optical designs is so great that many useful applications of any one material might be found and emphasized.

7.8.1 General Considerations of the Optical Properties Needed in Photographic Lens Design

It is worth while to point out here a few generalities gained from NDRC experience, likely to be valuable in further work. There exists no single rule governing the utility of a given optical material. However, if comments can be confined to the subject of photographic lens design, it becomes possible to isolate a few guiding principles.

Quite frequently in wide-angle systems it is necessary to use strong meniscus lenses, curved around a central stop. The smaller the field angle, the less important it becomes to curve the lens elements around the stop, and the more important it becomes to maintain a short lens barrel relative to the equivalent focal length. Then for relatively small angular fields, where higher order astigmatism is of no special consequence, diminishing to the microscope requirements for negligible fields for which even primary astigmatism is usually neglected, the lens barrel once more can become lengthened for the sake of additional lens speed and optimum spherical correction. In the wide-angle type of lens, particularly where it is desired to obtain increased speed, it is important to use high-index positive materials and to use as thin lens elements as practicable from a design point of view. It should be noted that there exists a fairly uniform progression from wide-angle systems strongly curved around a stop to microscope systems, whose surfaces more nearly conform to advancing wave fronts, in order that the sine theorem be satisfied at extreme convergence angles.

For lens systems corrected for distortion, it is necessary to make numerous compromises for the purpose of maintaining speed and angular field. There is no doubt that rare-earth glass or any material of similar index is of considerable importance in such an application. The standard Aero-Ektar $f/2.5$ lens makes good use of rare-earth glass elements to obtain coincidence of tangential and radial field curvatures to the very corner of its 5x5 picture size. This type of field correction is very much to be desired and represents a distinct advance over the usual correction involving astigmatic differences for the purpose of flattening the mean field. The chief aberration of the Aero-Ektar is oblique spherical aberration which is characteristic of designs based on the Opic or Biotar prototypes.

The ν-value of rare-earth glass is usually still too low to please a lens designer. The use of a positive material like spinel would make available a whole variety of indices for the negative elements, capable of overall color correction with favorable curves.

Any positive element in a lens system occupying a position of large incident ray height will profit by having relatively high index. If at the same time its ν-value is high, it becomes more possible with existing negative materials to obtain satisfactory color correction along with low index for a favorable Petzval sum. As the relative height of the ray becomes smaller

in the system, the importance of the high index diminishes. In any given situation the high-index material for a positive element is generally better, but the degree of improvement depends on the ray height and the requirement. Similar comments obtain for negative elements. At large ray heights, considerable gain for the Petzval sum is obtained by use of low index. At small ray heights, it is generally more profitable to use high-index negative materials.

Very often, thickness or air space in a strongly converging or diverging beam is of greater advantage than the high index, particularly for fast lenses of small coverage. Then again, use of a low-index negative material generally near the stop in a symmetrical system with its resulting steep curves, produces better field corrections than a high-index material. For lenses of wide angular coverage, great lens thickness for the purpose of gaining power is usually a source of large astigmatism of higher order. In turn, the introduction of negative materials like the alkaline halides with their very low ν-values will make color correction fairly easy when used with materials of intermediate ν-value.

In systems requiring an exceptionally good correction for spherical achromatism, it is often necessary to adjust the ν-values of positive and negative materials according to the various vergences of the system. No fixed rule can be applied, inasmuch as the monochromatic correction can lead to such a variety of forms. It is obviously advantageous in such a problem, and in fact in all problems, to have at hand numerous materials of high quality covering the diagram of index versus ν-value. It is by no means imperative that positive elements have high indices of refraction. Very many successful designs developed under NDRC in the war have inverted pairing and obtain correction of the Petzval sum by air spacing and lens powers. The Zeiss Telikon and the NDRC 36-in. wide-angle telephoto make use of such normal or old-style achromats. It is of interest to note that many successful NDRC lenses might have been constructed in 1885, in so far as use of glass types is concerned.

Generally speaking, at low relative heights in the lens system, the index of the negative element must be high, rather than low for best results. Also, the flatter curvatures that often accompany high-index negative elements tend to favor zonal spherical correction in narrow-angle systems. Finally, the paired old-style achromat often keeps oblique spherical aberration and higher order astigmatism under control.

One of the very remiss features of the optical industry in the United States is the universal failure to describe the physical properties of various types of filter and optical glasses. Even in German catalogs the ultraviolet and infrared transmissions for optical glass are omitted. Except for usual experience, the optical designer either works by analogy with German or English literature, or by guess. For military purposes, data required are transmission, precise indices of refraction at all accessible wavelengths, hardness, and durability. Less important are striation and bubbles, except for special applications, but these properties should be given also. The thermal properties, including volume expansion and change of index should be noted. Finally, some idea of relative costs, reproducibility, availability, and volume of production should be given. Too much detail is far better than too little in optical design work. It is to be regretted that no project under NDRC existed for the determination and reporting of such data to all optical designers. It is strongly recommended that the Armed Services sponsor the procurement of such data, including experiences in the field, preferably by a laboratory divorced from commercial considerations.

7.9 RECOMMENDATIONS BY NDRC

1. A method for growing single crystals should be developed. This can probably be done without any considerable change in present technique. Single crystals would be desirable, partly to reduce strain which may be impossible to remove by annealing, and partly to facilitate the production of a uniform figure on a polished surface.

2. Larger crystals of fluorite should be grown as soon as possible, since there are nu-

merous applications for which they could be used to advantage.

3. The technique for growing crystals of barium fluoride should be developed further, in view of the fact that this material will probably be superior to fluorite for optical applications. Its transmission throughout the spectrum should be measured accurately as soon as possible, since preliminary measurements indicate considerable absorption, even in the visible part of the spectrum. Quite possibly these measurements are not representative of average crystals free from impurities.

4. The most effective annealing schedule for fluorite crystals should be fully investigated. Particular attention should be given to the question whether it is possible, by any schedule of annealing, to relieve strains set up at the interfaces of individual crystals. These studies should be carried out on a quantitative basis, with measurements of strain made in various parts of the crystal before and after each run in the annealing furnace.

5. Further studies should be made to determine whether synthetic calcium fluoride can be used as the raw material. Particular attention should be given to various methods for eliminating adsorbed water.

6. Programs should be undertaken that aim at making other crystals available in large sizes for optical use, including spinel in particular and some of the alkaline halides. It is to be hoped that rare-earth glass will soon be available for general use in large sizes.

Chapter 8

OPTICAL PLASTICS

By *Sidney W. McCuskey*[a]

8.1 INTRODUCTION

THE HEAVY BURDEN imposed on the optical industry by the demand for fire-control instruments in great numbers led the NDRC in 1940 to investigate plastic substitutes for glass. The objectives of the program, undertaken by the Polaroid Corporation, may be summarized as follows:

1. To supplement the supply of optical glass with improved optical plastics.
2. To devise methods of manufacture of optical parts using unskilled or semi-skilled labor not drawn from the optical industry.
3. To synthesize new plastics in the hope of overcoming objectionable features of those currently in use.

Optical designers are constantly on the lookout for materials which provide unusual combinations of index of refraction and reciprocal dispersion (ν-value). Furthermore, in the design of many instruments lens surfaces of high curvature and of aspheric shape are highly desirable. Limitations of glass in meeting these requirements are well known and the use of plastics was considered worth investigating.

Plastic materials available in 1940 for optical purposes, primarily methyl methacrylate and styrene, had many disadvantages. Among these the most important were: inhomogeneity, high water-absorption, surface inaccuracy, imperfect retention of figure, high temperature coefficients of refractive index and of expansion, low softening temperatures and low abrasion resistance. Some of these disadvantages have been overcome by the use of new materials and others have been circumvented by new design. Optical plastic elements for instruments with moderate magnification and average field of view can now be made with a quality which is at least comparable with that of corresponding optical glass systems.

CHM and Styrene. The chemical and fabrication research to be described in the following pages yielded two plastics having properties suitable for precision optical parts, namely, polycyclohexylmethacrylate [CHM] and polystyrene [styrene]. All fire-control instruments designed and manufactured by Polaroid employed one or both of these plastics in the optical system. They are well adapted to the production of achromatized doublets, as is evidenced by their optical constants: CHM, n_D = 1.50645, ν-value 56.9; styrene, n_D = 1.59165, ν-value 31.0. Thus CHM corresponds to crown and styrene to flint in a glass combination.

Both of these plastics are linear polymers. CHM is very similar to methyl methacrylate, commercially known as Lucite. Polystyrene as used for optical elements is a highly purified form of the styrene which has been found useful for many other purposes. CHM is superior to its predecessors in having low water-absorption, as well as a shrinkage on polymerization of only 12.5 per cent against 22 per cent for methyl methacrylate. Its high boiling point, 210 C, makes possible polymerization at a higher temperature without causing bubbles due to boiling. As a result, CHM can be cast with satisfactory internal and surface homogeneity. It has a low softening temperature, however (about 70 C) and is easily scratched.

Although styrene has somewhat higher shrinkage (16 per cent) and has a yellowish tinge when cast, it is the best high-index plastic thus far found.

The details of research in the chemistry and fabrication of optical plastics as carried on by the NDRC contractor will be given in the following pages.

8.2 CHEMICAL RESEARCH

Little has been published on the possibilities of methacrylic compounds and styrene as sub-

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stitutes for glass in the manufacture of optical elements. It is known, however, that the excellent optical properties of both the methacrylates and styrene were recognized. A. H. Pfund[1] of Johns Hopkins University made dispersion measurements on a 30-degree prism ground and polished from methyl methacrylate polymers prepared by the E. I. Du Pont de Nemours Company. The refractive index n_D was found to be 1.4893, and the dispersion $n_F - n_C$ was 0.0085. The ν-value was calculated as 57.6. However, the results of any other investigations which may have been made on the optical properties of this material were not stated.

The possibility of polymerizing methyl methacrylate at high temperatures, especially under pressure, in glass molds was recognized as early as 1936.[2] A similar molding process was developed in 1937,[3] wherein monomeric methyl methacrylate is heated with a polymerizing catalyst, such as benzoyl peroxide, to form a partially polymerized ester which is subsequently completely polymerized under heat between glass plates.

However, the specific application of methyl methacrylate and styrene to the manufacture of optical elements had been mentioned but little, if at all, prior to 1940. Ellis' comprehensive article on polystyrene,[4] which discusses a large variety of uses of the material, does not specifically mention the possibility of its use in optical elements.

8.2.1 Glasses—Inorganic and Organic

Optical Properties of Matter

The optical properties of matter are dependent upon the interaction of the atoms and ions of a given material with light. The theory of dispersion of light by matter connects this interaction with the electronic structure of the atoms and ions involved and with their geometrical arrangement in the substance under consideration. The complex index of refraction combines the two interactions, which are usually considered separately as *absorption* and *diffraction*. Optical systems, in general, should exhibit as little absorption as possible for the wavelengths of light (ultraviolet, visible, or infrared) for which they are designed, except in the case of filters in which an exactly controlled absorption is required within a certain spectral range. Absorption takes place if certain electrons of the atoms, ions, or molecules in the material are raised to a higher energy level by absorbing a light quantum of the incident radiation. Diffraction is the scattering of light by the elementary particles of the substance under consideration and depends upon their polarizability.

Inorganic Optical Materials. Inorganic glasses of manifold chemical composition have served for optical purposes successfully for a long time. They consist in principle of a framework of silicon and oxygen atoms, in which are embedded ions of various metals, mostly belonging to the alkalis or alkaline earths. The silicon-oxygen skeleton furnishes a solid backbone of the whole structure, particularly for hardness and high softening range, and the ions which are distributed in the framework permit the adjustment of the refractive index and the dispersion of the system within certain limits.

The energy of dissociation of an Si-O bond in silica is comparatively high, namely, 89.3 kcal per mol and, because of the small atomic (or ionic) volume of silicon and oxygen (the ionic radii are 0.39 A and 1.32 A respectively), the specific spatial bond density is very high. The consequences are high softening point, low coefficient of thermal expansion, low compressibility, and great surface hardness, all factors favorable for the use of such systems in the construction of precision optical elements. On the other hand, the tetravalency of silicon and the divalency of oxygen results in the existence of a dense three-dimensional network of strong bonds, which is not favorable for the release of stresses and for the quick dissipation of mechanical energy within the system. Therefore, very careful annealing or tempering is necessary to obtain glass optical elements free of strain and even these still exhibit a considerable degree of brittleness.

Organic Optical Materials. The technology of organic high polymers has recently been developed to the point of yielding materials which possess a number of properties valuable for the

[redacted]

production of optical elements. These polymers consist of a backbone of carbon-carbon bonds, which have a dissociation energy of about 72 kcal per mol, and, if three-dimensionally extended throughout space, lead to the very dense and tough lattice of diamond. If two of the four valences of each carbon atom are not saturated by another carbon atom, but are occupied by hydrogen or other substituents, such as OH, NH_2, Cl, CH_3, C_6H_6, long chain molecules result which are held together internally by covalent bonds of high dissociation energy (70 to 90 kcal). The cohesion of the chains with each other is effected by van der Waals forces, having dissociation energies between 4 and 10 kcal per mol. Because two kinds of forces are responsible for the cohesion of such systems and because the hydrogen atoms or other substituents along the chain molecules have a certain degree of bulkiness or space requirement, the specific bond density in such organic polymers is not as high as in inorganic glasses. Therefore, organic glasses have lower softening temperatures, higher coefficients of thermal expansion, higher compressibility, and lower surface hardness but, because of the absence of elements of a high atomic number, are much lighter than their inorganic counterparts.

These organic glasses can be made from many easily available materials and can be polymerized in various ways. They can be cast or molded with a considerable degree of accuracy, have little residual color, and can be obtained in a high degree of clarity. The absorption and refraction of such organic polymers can be varied over a wide range by introducing either elements of a high atomic number or by distributing along the main valence chains organic groups or residues of high polarizability, such as conjugated double bonds or condensed aromatic ring systems. Typical of these plastics are polystyrene, polymethyl methacrylate, and polyvinyl acetate, which have been used for many kinds of optical elements of low precision, such as goggles, cheap camera lenses, and similar products.

8.2.2 Aims of the Research

In the research directed at the use of these or analogous materials in the production of precision optical elements, the basic tenets thought mandatory for success were:

1. Use of raw materials of the utmost purity.
2. Careful exclusion of dust and dirt from every part of the chemical and fabrication process.
3. Adjustment of the elementary optical properties such as refraction and dispersion to the required qualities by incorporating the proper chemical elements or groups into the monomer or monomers.
4. Regulation of the mechanical and thermal properties of the material by obtaining the proper bond density and the most favorable nature of the covalent backbone by controlling the degree of cross-linking in the system.
5. The obtaining of a sufficient chemical resistance and dimensional stability against moisture absorption by avoiding the presence of too many hydrophilic groups or by protecting such groups with the aid of large lipophilic residues, such as cyclohexyl, isobutyl, and the like.
6. The carrying out of the polymerization reaction in such small and controlled steps that there result optical elements containing a minimum of frozen-in strains.

8.2.3 Properties Demanded of Optical Plastics

The following are the requirements which any plastic must fulfill to be satisfactory for casting into precision optical elements:

1. *Homogeneity.* Refractive index constant throughout a given sample within 2×10^{-5}. Striae, bubbles, and other local defects substantially absent.
2. *Transparency.* High transmission (for most applications, 90 per cent or more per 10-cm path).
3. *Freedom from haze.*
4. *Reproducibility with respect to refractive index and v-value.*
5. *Freedom from color.* Nonselective transmission of light, at least over all the visible wavelengths, and in the ultraviolet.

[redacted]

6. *Stability.* Stable to heat, light, and ultraviolet radiation.

7. *Toughness.* Shatter resistant.

8. *Hardness.* Capable of receiving and holding optical finish and the desired figure. High scratch resistance desirable but not absolutely necessary.

9. *Low polymerization shrinkage.* Low shrinkage during polymerization contributes to the avoidance of strain.

10. *Ease of polymerization.* (a) Rapid polymerization, (b) homogeneous polymerization, which requires that the polymer be soluble in the monomer, and (c) high boiling point of monomer, to allow rapid polymerization at comparatively high temperatures without boiling and the consequent occurrence of bubbles.

11. *Ease of synthesis.* Methods of chemical synthesis amenable to quantity production.

12. *Availability of raw materials.* Raw materials preferably readily available in current market.

13. *Water absorption.* Absorption must be low enough to have a negligible effect on the refractive index of the material.

8.2.4 The Problem of Inhomogeneity

Visible inhomogeneity was associated with variations of refractive index within the resins and was readily observed at the peripheries of samples of methyl methacrylate which were polymerized in cylindrical bottles. Three factors probably account for most of the lack of homogeneity.

Monomer Loss

Since polymerization is a reaction which does not go entirely to completion, it is possible that some monomer remains to plasticize the polymers. The inhomogeneity of the resins may be caused by a more rapid evaporation of the residual monomer from the surfaces of the polymers than by diffusion through the masses to the surfaces. If the evaporation at the surfaces proceeds at a faster rate than diffusion from the center to the surface, then the material at the surface will differ from that at the center of the mass.

Many efforts were made to rid the castings of residual monomer. Monomeric methyl methacrylate was polymerized through heating under high vacuum, but this method proved slow and awkward and never fully succeeded in ridding the sample of monomer. An attempt was then made to vacuum and heat dry a fine molding powder, with the idea that the residual monomer could be driven more readily from the increased surface area of the powdered polymer. Successive weight measurements of the treated powder indicated substantial freedom from monomer. However, it was found impossible to mold the powder into a completely homogeneous mass; complete fusion of the particles was never obtained.

Absorption of Water

Since the atmosphere in which the material exists is constantly changing in temperature and relative humidity, the plastic is, with respect to its water content, seldom at equilibrium with its surroundings. Where water is absorbed in the plastic, a change in refractive index may occur. This change is a complicated phenomenon; one cannot predict even its direction. In the case of methyl methacrylate, we might expect the refractive index of the final product to be decreased, since the refractive index of water is lower than that of the compound. Curiously, the index often increases instead. The material becomes denser and serious inhomogeneity arises.

The absorption of water either from the vapor phase or from liquid water can be caused by two different phenomena.

1. If there are hydrophilic groups such as OH, NH_2, COOH, CONH distributed throughout the polymer, a certain amount of true solution of water takes place. In such cases a reversible equilibrium is established between the water in the vapor phase outside the polymer and the water inside it. Any change of the partial pressure outside is followed by a change of the equilibrium moisture content of the polymer. Because of the slowness of diffusion, there is usually a considerable lapse of time before the equilibrium moisture content is reached. Polymers having high solvent power for water, therefore, change such properties as density,

refractive index, modulus of elasticity, slowly and uncontrollably as the outside conditions change. Hence, high water solubility is unfavorable to the use of a polymer for optical purposes.

The ultimate cause of high moisture content at equilibrium is the capacity of the atomic groups mentioned above to bind water with considerable strength. In many cases the bond between the polar group of the polymer and the water exceeds considerably the normal van der Waals attraction, and in the case of cellulose and water can be as high as 16 kcal per mol. As it is sometimes impossible to avoid completely the presence of such polar groups, because they contribute to the refractive index of the material, the working hypothesis has been formulated that one might successfully protect such polar groups in a polymer against the access of the water molecules by a hydrocarbon shield. This "shield" hypothesis has been very useful in achieving lower moisture content, and, in particular, has led to the development of cyclohexylmethacrylate for optical purposes. Its guidance in any continuation of this work is recommended.

2. In many polymer systems of colloidal nature there exists another mechanism for water absorption, namely, the capillary condensation of vapor inside the submicroscopic cavities of the polymerized substance. This type of water binding is of great importance for fibers and films, but there is no indication that in highly consolidated systems any such capillary condensation has taken place.

Variations in Cross-Linking

Another cause for inhomogeneities in the molded polymer, which seems to be particularly important in the case of cross-linked resins, should be mentioned. The polymers ordinarily associated with plastics of the type discussed here consist of long chains of molecules. They are the so-called linear polymers. Cross-linked polymers, on the other hand, are those in which the chainlike structures are bound together by interlocking molecules at various points. If not very carefully controlled, cross-linking may proceed too rapidly within certain parts of the polymerizing mass and may produce material of higher density than in the surrounding region. Variation in the refractive index of the optical element may result. Such localized formation of highly cross-linked fractions has been observed in the polymerization of butadiene and other conjugated monomers and has offered considerable difficulty in making completely homogeneous polymers.

8.2.5 Cyclohexylmethacrylate

Cyclohexylmethacrylate[5] was used to test the foregoing theory of shields. Disks 1 in. in diameter and approximately $\frac{1}{8}$ in. thick, of polymerized methyl methacrylate and of CHM respectively, were weighed, immersed in boiling water for 1 hr, removed, and weighed again. The methyl methacrylate disks absorbed approximately 1 per cent of their weight in water, indicating a comparatively high degree of water absorption, while those of CHM absorbed one-tenth as much. This is approximately the same as the value for styrene, which had previously been considered unique in its property of low water absorption. There was no observable inhomogeneity at the periphery of the CHM cylinders.

This result would seem to indicate that the main factor correlated with inhomogeneity is water absorption. At least two supplementary explanations exist, however, to account for the superior homogeneity of CHM. The first is that the volatility of CHM monomer is considerably lower than that of monomeric methyl methacrylate. This may mean that any residual monomer in the polymer vaporizes from the surface at a rate sufficiently slow to allow the monomer to diffuse evenly throughout the entire mass.

A possible supplementary explanation is that CHM polymerizes more completely than does methyl methacrylate under the conditions available for promoting polymerization. It is not always easy to prove that one compound polymerizes more fully than another, and with CHM proof is lacking.

Whichever explanation is correct, theory and practice require that it be possible to synthesize a monomer which has a high boiling point (and

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low volatility) and which is capable of casting a nonpolar shield about the carboxyl group in the molecule. The methacrylates fulfill these conditions better than other types of resins and hence the chemical research has been concentrated primarily upon their production. Among methacrylates other than methyl and cyclohexyl, which achieve these two conditions, may be mentioned phenyl, menthyl, and benzyl methacrylate and their substitution products.

To predict low water absorption, a generalization which seems well sustained in practice is that the ester will be much less soluble, and its polymer for all practical purposes insoluble, when the alcohol from which the ester is synthesized has low water solubility.

Other advantages which accrue with an ester of the type just described include a comparatively low shrinkage during polymerization. Shrinkage is smaller because the reactive part of the monomer ester is a smaller fraction of the monomer molecule. It may be noted that the molecular shrinkage of all the methacrylates is approximately the same, but that the molecular weight of CHM is 1.68 times that of methyl methacrylate. The shrinkage of CHM (12.5 per cent) is thus proportionately less than that of methyl methacrylate (22 per cent). A low shrinkage during polymerization results in simplification of the problems of fabrication because of less physical distortion and shrinkage of the resin in the mold.

A further advantage of esters with high molecular weights, such as CHM, lies in their high boiling points (210 C for CHM as compared with 100 C for methyl methacrylate). A high boiling point makes it possible for polymerization to take place at higher temperatures without causing bubbles due to boiling.

As a result of these advantages, when CHM is cast, local inhomogeneities, such as striae and bubbles, and premature separation from the mold, can be largely overcome. Styrene, when employed in a purified form, likewise can be cast with satisfactory homogeneity. In the forming of polymeric masses, the manufacture of organic resins achieves greater efficiency than is possible with inorganic glass, where the percentage of glass which must be rejected is very high, especially with large masses.

8.2.6 Styrene

CHM must be supplemented for optical design purposes by another resin. For simple achromats and for Porro prisms, a high index of refraction is required.

Styrene possesses a relatively high index ($n_D = 1.59165$). It is readily available in quantity at low cost, with no prospect of ultimate shortages. Its water absorption is about the same as that of CHM. It is tough and transparent. Shrinkage during polymerization amounts to 16 per cent. While this is a fairly large shrinkage, styrene has relatively low viscosity for a given concentration of polymer in monomer, and this permits successful fabrication.

For these reasons, styrene was selected as a high-index material. Unpurified styrene unfortunately possesses certain defects. It is softer than methyl methacrylate and CHM, and even in small masses has a faint yellowish tinge and a small amount of haze. When fabricated, it tends to craze or crackle at the surface. Its rate of polymerization is slow, thus lengthening the time cycle required per unit to prepare the optical elements.

Purified Styrene. The use of purified styrene, when combined with special polymerization procedures, successfully avoids serious yellowish tinge and reduces haze considerably, although residual amounts are noticeable in large-sized optical elements. A method for purifying styrene will be described later.

8.2.7 Synthesis of Other Plastics

While CHM and styrene formed the combination of plastics most suitable for optical systems, a large amount of chemical research was devoted to the synthesis of other materials. In general the objectives of this research were:

1. To find plastic materials having unusual combinations of refractive index and ν-value. A plastic having a high index and at the same time a high ν-value would have distinct advantages in the design of optical systems. Something comparable to dense barium crown glass was sought.

2. To replace styrene with a material having less shrinkage and haze and which would polymerize more rapidly so that a shorter baking cycle could be employed.

3. To provide a plastic with unusually low ν-value (less than 25), a characteristic desirable in the use of the material for achromatization of wide-angle eyepieces.

4. To find plastics with low thermal expansion coefficients and more resistance to abrasion than those in current use.

In the course of the research, 113 compounds[6] were synthesized and their physical properties studied. Of these, 78 were obtained in a condition permitting their indices of refraction and ν-values to be measured. They range in index from 1.65 to 1.44 and in ν-value from 21 to 59, ranges comparable to those for optical glass. In fact the same nearly linear relationship exists between ν-value and refractive index for plastic materials as for glasses. It is interesting to note that the refractive indices of the methacrylates can be predicted prior to synthesis from the density of the material and its atomic refractivity.[6a]

High-Index, High-ν Materials

An attempt to produce materials having unusual optical properties was begun by introducing other chemical elements either directly in the monomer molecule or as homogeneous plasticizers. It was thought that since most common organic resins tend to follow an average refractive index-ν curve very closely, a different class of elements might affect the optical properties of the resulting compounds. The following investigations were undertaken:

1. *Silicon.* Silicon was introduced in the form of triethoxy silicol methacrylate. This element lowered the index for a given ν-value rather than raising it.

2. *Heavy Metals.* Attempts were made to introduce heavy metals, first through a nonpolar linkage in a polymerizable molecule. An example of such an attempt is the lead derivative of methacryl acetoacetate. This type of compound failed to polymerize.

In addition to polymerizable molecules, one nonpolar linkage of the plasticizer type was investigated. A lead derivative of diethyl dithiophosphate was introduced into the monomer. This lead derivative, however, proved to be insoluble in the monomer.

A plasticizer type which was soluble in the monomer was lead diethyl dithiophosphate. About 10 per cent of this compound dissolved in common monomers. Unfortunately it proved to be an effective polymerization inhibitor.

In addition to attempting to introduce various heavy metals through nonpolar linkages, one polar-linked, heavy metal compound has been synthesized. This is a lead methacrylate compound which shows a high index, but is not markedly off the average index-ν curve.

3. *Sulfur.* A third attempt consisted in introducing sulfur into monomers. Sulfides and vinyl sulfonic esters were considered. In some compounds, such as vinyl phenyl sulfide, the introduction of this element has resulted in a high index without much change in the ν-value, so that the resulting compound lies well off the index-ν curve.

4. *Nitrogen.* Another element introduced into monomers is nitrogen. In the form of nitro compounds, it lowered the ν-value for a given index. An example of this is nitromethyl-propyl methacrylate. In the form of amino compounds it raised the ν-value for a given index. An example of this is β-amino-ethyl methacrylate. Other examples are the N-substituted methacrylamides. With these, the index is raised over that of the corresponding ester by 0.03 to 0.04 but the ν-value is relatively unaffected.

5. *Ether Linkages.* Monomers containing ether linkages were investigated in seeking to raise the ν-value for a given refractive index. Until very recently, results with ether linkages have proved disappointing. One or two causes may have contributed to this failure: either an inhibitor effect or a lowering of the density of the compound or both. In general, it was found that systems containing ether linkages lead to soft and rubbery polymers. Whether this is due to incomplete polymerization because of an inhibitive action of the ether linkage or whether this is an intrinsic property even of very highly polymerized samples cannot yet be stated. The materials investigated would be too soft for use as lenses, prisms, or optical flats. Ether linkages, in general, lower the

density of the compound considerably, with a consequent lowering of index. Thus, while the ν-value may be raised considerably, it is accompanied by a lower refractive index.

6. *Increasing Alicyclic Rings.* Another approach toward raising both index and ν-value was made through increasing the number of alicyclic rings contained in the alcohol part of the methacrylic ester. CHM has an index higher than that of methyl methacrylate with no appreciable change in ν-value. Following this trend further, cyclohexyl cyclohexylmethacrylate was synthesized, and here the index was raised somewhat with little change in ν-value. Cyclohexyl cyclohexylmethacrylate appears to mark the practical limit to which this procedure can be carried, however. Bornyl methacrylate was synthesized and, although it has three alicyclic rings, it showed no improvement over CHM in departing from the index-ν curve.

7. *Other Methods.* Three other methods of producing a high-index plastic with high-ν value also yielded negative results. Substitution of other radicals in the α-position of acrylic acid and copolymerization of two different monomers were tried without success. Inclusion of halogens in the molecules resulted in two compounds approaching the desired index and ν-values. These were methyl α-bromo acrylate ($n_D = 1.567$, $\nu = 46.5$) and 2, 3-di-bromopropyl methacrylate ($n_D = 1.57$, $\nu = 44$). Unfortunately, however, these materials were unstable and turned yellow very quickly.

It must be concluded, in summarizing the search for a plastic having unusual optical properties, that none was found in spite of the intensive program of research.

Replacement of Styrene

Simultaneously with the study of high-index, high-ν materials, an investigation of materials which might replace styrene was undertaken. The objectives were to discover a material harder than styrene, with less shrinkage, and which would polymerize more rapidly in order to shorten the baking cycle in production.

Materials investigated include styrene derivatives, some of the higher index methacrylates, and higher index vinyl esters. So far, no material of this group has proved sufficiently superior to styrene to warrant placing it in production.

An example of styrene derivatives is orthomethyl styrene. While this substance exhibits less shrinkage, greater hardness, and a higher ν-value than does styrene, it is somewhat difficult to synthesize, and it is not easy to handle, since it cannot be polymerized as fully as styrene before gelling.

An example of a high-index vinyl ester is vinyl benzoate. Its index and ν-value are nearly the same as those of styrene, and this material might well be substituted for styrene. It is comparatively easy to synthesize. It has not been successfully polymerized in mass, however, because it does not produce a sufficiently hard polymer when the temperature is kept low, and bubbles arise when the temperature is raised. A possible explanation of the bubbles is that at high temperature there is some decomposition of this ester to produce acetaldehyde.

Low-ν Materials

Certain problems of instrument design, such as the achromatization of wide-angle eyepieces, can be simplified by the use of a material with a ν-value of 25 or lower. In the course of the investigation of high-index materials, several compounds with low-ν values have been synthesized. They are listed in Table 1.

TABLE 1. Plastic materials with low ν-value.

Material	Index	ν-value
α-naphthyl methacrylate	1.641	20.5
N-vinyl phthalimide	1.619	24.1
Vinyl carbazole	1.683	18.8
α-naphthyl carbinyl methacrylate	1.63	25.0
9-fluorenyl methacrylate	1.63	23.1

The first of these plastics is the most suitable for optical purposes, in spite of difficulties involved in its fabrication. The yield of pure material is about 15 per cent in synthesis and there are at times variable amounts of yellow color in the polymer. Lack of homogeneity in the polymers of the remaining entries of Table 1 preclude their use on a large scale.

Hard and Thermally Stable Plastics

In an effort to increase the abrasion resistance of plastics and to remove objectionably

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high thermal expansion coefficients, research on cross-linked polymers has been undertaken. The use of cross-linked or 3-dimensional polymeric materials as optical plastics offers several advantages over linear polymers. Among the most important properties they possess are:

1. A relatively low coefficient of expansion (about one-third that of linear polymers).
2. High softening temperature (above 150 C).
3. High resistance to abrasion (the abrasion resistance of some cross-linked polymers, as measured in the falling silicon carbide test, is higher than that of glass).
4. High hardness (the hardness of ethylene dimethacrylate [EDM] for example, measures about Z-126, that of CHM about Z-109 by the Rockwell test).

In general, the synthesis of cross-linking monomers may be performed by the techniques developed for linear monomers which involve esterification of the alcohol. In the case of the cross-linking material, a polyhydroxy or an unsaturated alcohol is usually esterified with an unsaturated acid such as methacrylic acid in the presence of a suitable catalyst. However, the cross-linking materials usually have higher molecular weights than the monomers which give linear polymers, and, therefore, their boiling points are in general higher. This means that if the monomer is a liquid, distillation should be carried out under greatly reduced pressure (about 2 mm of Hg) in order to prevent polymerization in the still pot. This must be avoided at all cost, since even slight polymerization causes gelling and the eventual formation of insoluble, infusible material. In large-scale production of EDM, it is possible to work out conditions so that polymerization during distillation is prevented. It is felt that similar conditions could be devised for any such material. The yield of pure EDM by this synthetic method has been of the order of 50 per cent, which is comparable to the yield obtained in the preparation of CHM. Small amounts of cross-linking substances may also be obtained conveniently by esterification, using methacrylic anhydride in the presence of an aromatic base. It is also possible to prepare this type of compound by means of an ester interchange. For example, EDM may be prepared from methyl methacrylate and ethylene glycol, using sodium methoxide as a catalyst.

For other types of cross-linking materials, such as *p*-divinyl benzene, it is necessary to develop special syntheses. In general the synthetic methods employed are similar to those used for preparing the monofunctional analogs, for example *p*-divinyl benzene is prepared from terephthaldehyde. Cross-linking materials which contain unlike functions, such as allyl methacrylate, have been prepared by the ester interchange method.

No unusual difficulty has been encountered in the storage of cross-linking plastics provided they are kept at a temperature below 3 C. EDM and similar materials cannot be stored at room temperature. Batches of such materials have been kept for periods up to 3 months without decomposition or polymerization, except for methacrylic anhydride. If methacrylic anhydride is stored at -50 C, however, no polymerization seems to occur. It is good practice to store the cross-linking monomer without catalyst or inhibitor and to catalyze just before using.

EDM and Allyl Methacrylate. The two cross-linking plastics which have been investigated most extensively in connection with this problem are ethylene dimethacrylate and allyl methacrylate. These materials were chosen as being representative of the general classes suitable for optical purposes, with the idea that although they may not be suitable in all respects, they would at least indicate the general characteristics of the class. Since both compounds are relatively easy to synthesize, small pilot-scale syntheses have been developed.

When properly polymerized, EDM has a hardness of Z-126, a coefficient of expansion of 2.3×10^{-5} per degree centigrade, and does not distort in softening tests below 170 C. The specific gravity of the polymer is approximately 1.25 at 25 C. The main disadvantages of EDM are its rather high polymerization shrinkage (15.7 per cent) and high refractive index change upon absorption of water (about 0.005 in the 100 C 1-hr boiling test).

Allyl methacrylate, when polymerized properly, has a hardness of Z-126, a coefficient of expansion of 2.6×10^{-5} per degree centigrade,

and a distortion point above 170 C. The polymer has a specific gravity of 1.18 at 25 C. It has a polymerization shrinkage of 21.6 per cent, which is high compared to EDM, but may be reduced by partially polymerizing to a soluble linear polymer, dissolving in more monomer and then finishing the polymerization. Although allyl methacrylate absorbs about the same percentage of water as EDM, its index change is considerably less, about 0.0008 in the 100 C 1-hr boiling test.

TABLE 2. Evaluation ratings of optical plastics.

Characteristic	Perfect plastic	CHM	Styrene	Vinyl carbazole	β-amino ethyl methacrylate	Ethylene dimethacrylate	Allyl methacrylate	N-allyl methacrylamide	Vinyl methacrylate	Ethylidene dimethacrylate	p,p'-xylylenyl dimethacrylate	p-divinyl benzene
1. Homogeneity	15	15	14	6	5	12	12	10	9	14	12	10
2. Resistance to water absorption	10	9	9	9	1	6	6	5	6	5	6	10
3. Hardness	10	8	6	9	8	10	10	8	10	10	10	10
4. Softening temperature	8	6	6	8	7	8	8	7	8	8	8	8
5. Toughness	6	3	5	3	4	3	3	4	2	4	4	4
6. Absence of color	8	8	5	5	6	5	7	2	7	7	6	6
7. Ultraviolet stability	5	5	3	5	4	4	5	2	4	5	5	5
8. Ease of polymerization	5	5	3	5	3	5	3	2	4	5	5	5
9. Monomer boiling point	5	5	3	4	5	4	3	4	4	4	3	4
10. Low polymerization shrinkage	8	7	6	7	5	6	1	3	3	7	5	5
11. Degree of polymerization	8	5	8	5	5	1	1	2	1	1	1	1
12. Ease of monomer manufacture	12	8	11	10	7	8	8	7	3	11	6	2
	100	84	79	76	60	72	67	56	61	81	71	70
refractive index		1.5064	1.5916	1.683	1.537	1.5063	1.5196	1.5476	1.5129	1.4831	1.5559	1.6150
v-value		56.9	31.0	18.8	52.5	53.4	49.0	47	46	52.9	37	28.1

8.2.8 Evaluation of the Plastic Materials

In order to compare the substances synthesized, on a semi-quantitative basis, a rating scheme was devised on the basis of which a perfect plastic would be 100. These characteristics and their perfect ratings are shown in Table 2 together with the evaluations of CHM, styrene, and the nine plastics which at the conclusion of Contract OEMsr-70 showed the greatest promise for future utility. Methods of synthesis and suggestions for further research on these optical plastics are given in detail elsewhere.[6b]

ALLYL METHACRYLATE AS AN EXAMPLE

The significance of an appraisal of a plastic on the rating scheme shown in Table 2 can be judged best from an example showing the derivation of the numbers for one plastic. Consider, for example, allyl methacrylate:

1. Its homogeneity is high, but not as good as that of CHM or of styrene. Hence it was given a grade of 12 out of a possible 15.

2. Its resistance to water absorption is poor since 0.5 per cent by weight is absorbed upon boiling for 1 hr. The rating on this characteristic is therefore 6 out of 10.

3. The material is extremely hard; its rating is Z-125. Hence a maximum score of 10 is recorded for this characteristic.

4. Since the polymer decomposes before it softens, it was given a maximum rating 8 on this score also.

5. A property common to linear polymers, which cross-linked polymers do not possess to the same degree, is toughness or resistance to

shattering upon sudden impact. Hence, only 3 out of 6 points were given to this material.

6. Since this material has not yet been obtained as free from color as CHM, only 7 points out of 8 were assigned to it. This is presumably no intrinsic property of the plastic and might be considerably improved by further work.

7. The substance is as stable as any other organic resin to ultraviolet light, and therefore was assigned the highest rating.

8. Since allyl methacrylate has not yet been successfully partially polymerized in order to reduce polymerization shrinkage in the mold and must, at present, be cast directly from the monomer, it was rated only 3 out of a possible 5.

9. The substance boils at 55 C under 30 mm Hg pressure, and it is more difficult to prevent the escape of monomer than with CHM which boils at about 66 C at 3 mm Hg. Hence it was only rated 3 out of 5.

10. The shrinkage of this plastic upon polymerization amounts to not less than 21.6 per cent. This is exceedingly high and hence only 1 out of 8 points was assigned for this property.

11. Since only a very low molecular weight polymer can be prepared before casting, the material was given 1 out of a possible 8 points. This appeared at first to be a rather serious drawback, but improvement in technique finally led to the possibility of casting even this material without too much difficulty.

12. Two satisfactory methods for synthesizing allyl methacrylate have been worked out. But since the yields of pure product are only about 50 per cent, only 8 out of 12 possible points have been assigned for this characteristic.

8.3 CURRENT MANUFACTURING PRACTICE

The fabrication of plastic optical parts involves the techniques of solidifying the liquid monomers by polymerization and of imparting optical surfaces to the polymers. Two general methods have been tried in the fabrication research. The first consists in polymerizing a mass of material of roughly the shape desired for an optical part, and then grinding and polishing the blank. The second consists in casting the polymer in precision molds so that when the molds are removed the plastic surfaces are optically accurate and have a high surface polish.

Fabrication of blanks by the first of these methods leads to relatively strain-free and homogeneous optical units. Grinding and polishing by the usual methods of the glass industry are not very satisfactory when applied to plastic materials. The harder polymers such as allyl methacrylate, and the medium-hard materials such as CHM, can be ground with the compounds used for glass. Styrene, on the other hand, is soft and since it does not chip, standard cutting operations on a lathe or shaper are preferable.

None of the plastic surfaces, however, has been very successfully polished. It has been found that the quality of the final surface of an allyl methacrylate blank is definitely improved when the allyl methacrylate is copolymerized with 10 to 20 per cent of CHM. The CHM itself is too tough to polish well, although satisfactory surfaces have been achieved with it.

Press polishing has been tried, but the successive heating of the polymer to make it flow against the mold, and the cooling to separate it from the mold, results in strains and pitting which render the part useless from an optical standpoint.

Attempts to form optical elements by building up sections of relatively thin sheets of material and improvement of surfaces by the addition of thin surface layers of polymerized material have not been very successful.

In view of the difficulties involved in blanking and finishing optical elements and the time involved in the process, a casting technique has been developed in which the final surface and form of an optical part result directly. Experiments to this end are described elsewhere.[6c] The following pages will describe in some detail the methods of producing CHM and styrene optical elements.

8.3.1 Chemical Production of CHM Monomer

MATERIALS FOR SYNTHESIS

The materials for synthesis of CHM consist of 86 parts by weight of methacrylic acid, 100

parts cyclohexanol, 6 parts *p*-toluene sulfonic acid, about 5 parts pyrogallol, and about 80 parts benzene. The *p*-toluene sulfonic acid serves as esterification catalyst, the pyrogallol as polymerization inhibitor. The benzene carries off the water of reaction as formed. The quality of the materials required is as follows:

1. Methacrylic acid: Index of refraction between 1.4306 and 1.4315 at 20 C; contains 0.1 per cent by weight pyrogallol inhibitor, added at the time of synthesis by the manufacturer.
2. Cyclohexanol: Barrett's commercial grade, minimum purity of 99.25 per cent.
3. *p*-toluene sulfonic acid, monohydrated: Eastman organic chemicals purest grade.
4. Benzene: Technical grade; no special precautions to guard against thiophene or other sulfur-bearing compounds.
5. Pyrogallol: Chemically pure.

For a representative synthesis the quantities required are 38.01 kg methacrylic acid, 44.23 kg cyclohexanol.

PREPARATION OF THE CHARGE

A charge of the foregoing materials, after being thoroughly mixed, is reacted at atmospheric pressure for 15 to 18 hr during which time the pot temperature of the charge rises from 105 to 115 C. Crude CHM results.

The reactor is a 30-gal copper-jacketed kettle containing copper coils both inside the tank and in the jacket through which water, heated by a boiler and controlled by an aquastat at 127 C, circulates. Above the copper reactor is a column 6 in. in diameter packed with copper mesh. Vapor from the top of the column is led to a total condenser and then into a separator, which retains the water distilled over in the reaction, but permits the benzene distilled over to return to the reactor.

Water is removed periodically from the separator in order to follow the stage of the reaction. Esterification is judged to be complete when the amount of water of reaction approximates the theoretical yield, which, for the above charge, is 8,250 cu cm.

An excess (1.02 kg) of cp sodium carbonate, monohydrated, is then added to the reaction mixture to neutralize the esterification catalyst, *p*-toluene sulfonic acid. During this neutralization process, the heating system is turned off and the reactor vessel is allowed to cool. The heating system is again started and the water of neutralization distilled off.

The benzene (the vehicle for carrying over the water of reaction) is now removed by distillation; first, at atmospheric pressure and then at decreasing pressure as the concentration of benzene decreases, until an absolute pressure of 25 mm Hg is obtained. At this point, the charge in the reactor is cooled by circulating cold water through the jacket and coils previously used for heating. (The heating system is so designed that if the reactor temperature goes above a predetermined level, cold water can be circulated to check the reaction).

After the liquid cools, the charge is pumped through a standard Sweetland pressure filter into a 20-gal copper reservoir. Additional pyrogallol (0.454 kg) is added at this point. The material is then filtered and distilled until the proper fraction, which has a boiling point of 60 C at 2 mm Hg, is obtained.

CHM can be stored at 4.5 C, probably indefinitely, if the fraction of the pyrogallol inhibitor which distills over with the product is not removed. It has been stored at this temperature for 18 months without observable ill effects.

Before use, the product is further purified by removal of the inhibitor by extraction with a sodium hydroxide solution. The charge flows by gravity from the reservoir into a 20-gal copper kettle equipped with coils and jacket, similar to the reactor. Above the kettle is a packed column consisting of a 5-ft section of glass pipe 3 in. in diameter, with cups of stainless steel screening fitted tightly within the glass pipe. Above the column are located a thermometer and a tap for measuring the absolute pressure of the system at the thermometer well. A condenser is attached, composed of 1.5 in. glass pipe, equipped with a cooling jacket and a glass coil within the pipe. Two 5-gal glass receivers are used for the condensate. The vacuum lines are so arranged that the lower receiver may be opened to the atmosphere in order to discharge the product while the rest of the system is under vacuum.

The charge is distilled under vacuum, until

the boiling point reaches 57 C at an absolute pressure of 2 mm Hg, at which stage collection of the pure material is commenced. At an absolute pressure of 20 mm Hg, the true boiling point of pure CHM is 60 C. If the boiling point of the material exceeds the true boiling point by 2 C, collection is stopped, and the material remaining in the kettle is rejected. The resulting CHM is stored in 5-gal glass bottles, tightly sealed, at 4.5 C.

REMOVAL OF INHIBITOR PRIOR TO USE

Forty liters of monomer are put into a 20-gal stainless steel mixing tank and washed with 15-l batches of 5 per cent aqueous sodium hydroxide solution until the aqueous layers of two consecutive washings are colorless. The monomer is then likewise washed with water to remove traces of the sodium hydroxide, until the pH of the wash water is approximately 7. The monomer is next transferred to 5-gal carboys, and one pound of cp anhydrous sodium sulfate is added to remove all traces of water. The pure monomer is decanted, filtered, and placed in tightly sealed glass flasks at 2 C. The purified material is stored no longer than one month before being used.

8.3.2 Purification of Styrene

Styrene, as purchased from the Dow Chemical Company, while 99.5 per cent pure, contains enough impurities, principally ethyl benzene, to preclude its use for plastic optical elements. Furthermore, 10 parts per million of p-tertiary butyl catechol are added by the manufacturer as an inhibitor to prevent polymerization.

The purification of this material is illustrated schematically in Figure 1. Forty liters of styrene are placed in a 20-gal stainless steel mixing tank, and washed three times with 15-l batches of a saturated aqueous solution of sodium bisulfite to remove oxidation products. The styrene is then washed three times with a 5 per cent aqueous solution of sodium carbonate to remove the polymerization inhibitor and other impurities. After the sodium carbonate is extracted by triple washing with water the material is distilled. The distillation apparatus consists of a 22-l round-bottom Pyrex flask to which a glass column 3½ ft high is attached. Connected to the column is a total condenser, followed by a Leighton fractionator and a 5-l receiving flask. The individual pieces of equipment are joined with tapered ground glass connections. Heat is supplied to the distilling flask by an electric heating mantle placed below the flask.

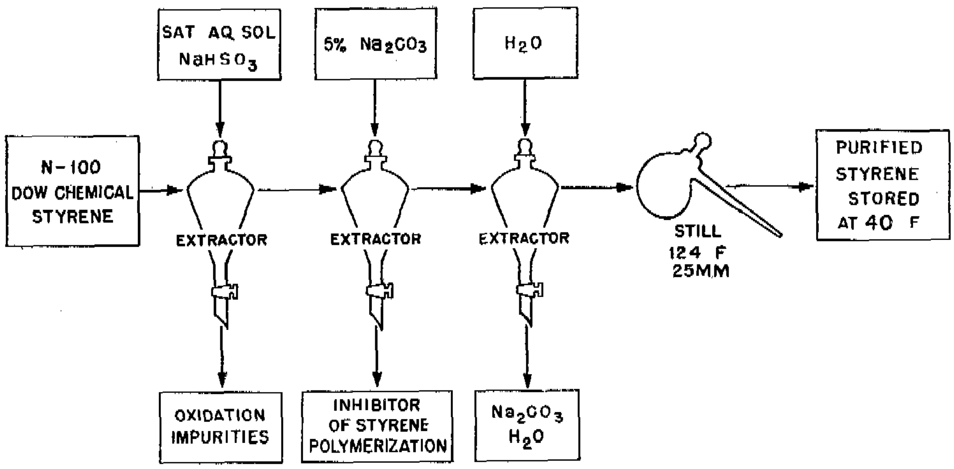


FIGURE 1. Schematic diagram showing steps in the purification of styrene.

Fifteen liters of the material are placed in the 22-l distillation flask. Distillation is carried out at a temperature of 50 C and a pressure of 25 mm Hg until only a small viscous residue remains in the distillation flask. The resulting pure styrene is stored at 4.5 C in glass flasks,

[redacted]

which are tightly sealed to keep out air and water vapor. The maximum storage period between purification and use is 3 days.

8.3.3 Casting Technique

Casting precise optical parts of plastic consists in polymerizing the liquid plastic-forming material against accurately surfaced mold walls. The procedure involves four basic steps: (1) partial polymerization, (2) preparation of the mold and injection of the polymer, (3) baking, and (4) removal from the mold. These are illustrated schematically in Figures 2 and 3.

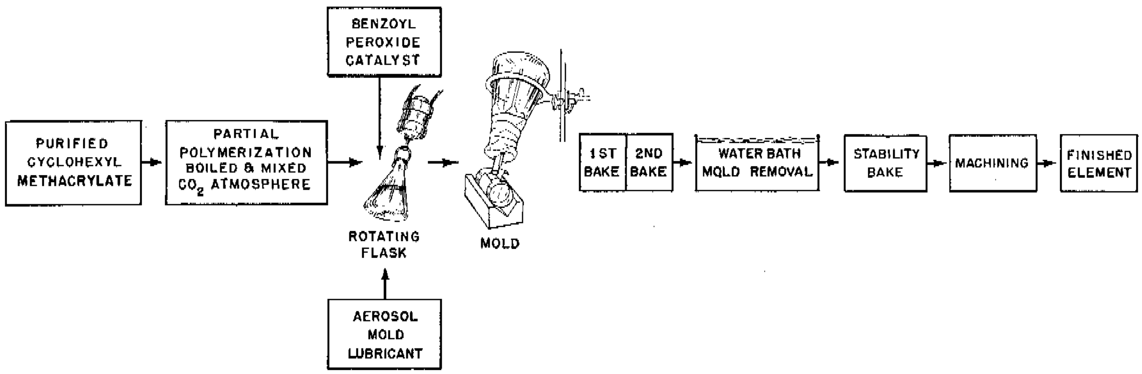


FIGURE 2. Polymerization and fabrication sequence for CHM.

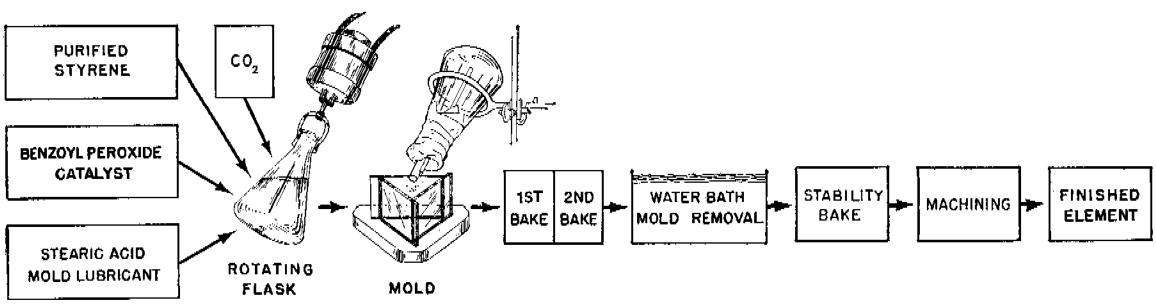


FIGURE 3. Polymerization and fabrication sequence for styrene.

PARTIAL POLYMERIZATION

The processing of the pure CHM monomer begins with polymerizing it until the viscosity is about 50,000 centipoises. The monomer, in 600 cu cm batches in wide-mouth Erlenmeyer flasks, is inspected for foreign matter and is then heated on hot plates at 330 to 340 C. After 2 min, the flasks are removed and the air within is displaced with filtered CO_2. The gas is introduced in such a way that no bubbles are formed in the monomer.

The flasks are returned to the hot plates and the contents heated at approximately 250 C for 15 min. During this time the CHM is not allowed to boil longer than 3 min. At the end of this heating, the flasks are removed and sealed airtight with cellophane and brown masking tape.

Thorough mixing of the partially polymerized mass is accomplished by rotating the flasks for 2 hr on specially constructed turntables and conveyor belts. A portion of the mixing is done in a cool water bath at 25 C.

After the mixing is complete, a solution containing a polymerization catalyst and mold lubricant is added. The solution consists of 1.8 g of benzoyl peroxide (0.3 per cent by weight) and 3 g of aerosol O.T. in 30 cu cm of CHM monomer. The benzoyl peroxide is purified from technical grade by dissolving it in acetone,

[redacted]

precipitating in water, filtering and drying under vacuum. The material is then mixed again for about 1 hr until all striations disappear. The flasks are sealed and stored in a refrigerator at 2 C until the partial polymer is to be cast.

The partial polymerization of styrene is carried out in much the same way as described above for CHM. More polymerization catalyst is necessary, however, for styrene. For prisms, 3 g (0.5 per cent by weight), and for lenses 6 g (1 per cent by weight) of benzoyl peroxide is added, together with 1.2 g of stearic acid as a mold lubricant. More catalyst is used in material for lenses because the greater ratio of surface to volume for these elements permits control of exothermic reaction at a greater polymerization rate. The mixing time is approximately 14 hr for the styrene containing 1 per cent benzoyl peroxide and 7 hr for that containing 0.5 per cent. It is preferable to cast styrene elements immediately after the thickening process has been completed, since overnight storage increases the haze in the cast product.

Preparation of Molds

Molds for casting lenses and prisms are designed to impart an accurate optical surface of high finish to the molded elements and to permit quantity production. Surface accuracy in the product depends to a considerable extent on the accuracy, surface finish, and alignment of the molds. Quantity production of optical elements requires that the molds be designed for long life, for reduction of unit cost, and for easy and quick assembly and disassembly.

The molds for lenses consist of solid, ground, and polished glass disks, one for each face of the desired lens. Pyrex glass is employed, its advantages over other kinds of glass residing in its strength, its resistance to scratches, its resistance to the dissolving action of water in the final bath in which the finished lenses are disengaged from the glass molds, its resistance to thermal shock, its low coefficient of expansion, and its availability. Because Pyrex is considerably harder than most glass, the manufacture of molds from it is somewhat more expensive than from other glass such as crown, which might be used. More abrasive is required, wear on diamond laps is greater, and polish is slightly more difficult to obtain.

Lenses for which spherical molds have been made range in diameter from $\frac{3}{4}$ to 5 in. Mold diameters are from 8 to 25 per cent larger than the lenses to be cast in them so as to allow for radial shrinkage and for poor alignment. The walls are 1 in. thick to preclude distortion during the final polymerization process. A locating groove is accurately ground in the circumference of the cylindrical side of each mold, the back side of the groove being accurately located

FIGURE 4. Assembly of lens molds.

at an established distance from the curved molding surface.

The mold surfaces are ground and polished to spherical form by the usual methods of the optical industry. Aspherical surfaces are ground on a specially constructed grinder which transfers a curve from a cam through a grinding wheel to the surface of the glass.

The grooved mold halves are mounted face to face in an assembly jig, which maintains them at the proper distance apart by registering the backs of the ground grooves against the stops of the jig. This assembly is shown in Figure 4. The stops are separated by a distance calculated to include the center thickness of

[redacted]

the desired lens plus the amount allowed for shrinkage during solidification (which depends on the material used). Allowance for shrinkage is $\frac{1}{10}$ in. or less for thin ($\frac{1}{4}$ in.) CHM lenses.

In order to complete the mold cavity, flexible tape is wrapped around the opening between the two mold halves and fastened to the polished edges. The tape provides a wall which is sufficiently rigid to hold the distance of separation set by the stops but is not too rigid to accommodate shrinkage during polymerization.

FIGURE 5. Assembly jig for rhombs.

The flexible tape consists of Jonflex Industrial Adhesive Tape combined with polyvinyl alcohol [PVA] sheeting. This sheeting is applied with a tape-rolling machine to the center portion of the adhesive surface of the Jonflex tape, sufficient adhesive being exposed on each side to produce a tight seal at the mold edges. The width of the PVA sheeting is slightly greater than that of the edge opening of the mold cavity. In this way the sheeting, which does not affect polymerization of the plastic material, prevents contact between the adhesive, which inhibits polymerization, and the material to be polymerized. The end of the tape is pulled back $\frac{1}{2}$ to 1 in. to form an opening for filling the mold cavity.

Prism molds consist of selected plate-glass side walls mounted on glass bases with solder applied at all joints. To make prisms for 6x30 binoculars, glass plate is selected having an accuracy of 2 fringes for a piece $1\frac{1}{2}$x$1\frac{3}{8}$ in. and 4 fringes for a piece $1\frac{1}{2}$x$1\frac{7}{8}$ in. The pieces with the broader tolerance are selected for Porro prisms where the plate on the hypotenuse requires more accuracy than on the legs. The difficulty of obtaining flat glass by selection increases with the size of the pieces required. The accuracy of the surfaces of plastic prisms molded with glass selected to 2 fringes is as high as can be attained at present. Specially ground and polished glass mold faces do not afford greater accuracy.

The thickness of the glass employed for small prism molds is $\frac{3}{8}$ in. Thinner glass bends slightly during the polymerization process. Quarter-inch plate is satisfactory for molding prisms or rhombs employed at unit power in offset devices.

The plate-glass walls are assembled upon jigs as shown in Figure 5; the shapes are those of the required prisms and rhombs. Jigs are made from steel blocks milled to the proper angles. For very accurate surfaces, the jigs are machined to as close a tolerance as possible, then are hardened, and ground and polished by hand to final shape. Measurements of angles in the last stages are made on a spectrometer. Jig surfaces have grooves to act as dust traps when the glass is slid into position, since the presence of dust can cause deviation in angles between faces greater than the allowed tolerances. Where tolerances of the angles must be held closely, say to 3 min of arc or less, as with Porro prisms or with the Offset Attachment Mark 8, closeness of contact is tested before soldering by examining interference fringes between glass and jig.

The glass walls are soldered at the corners while mounted on the jig, care being taken to keep the glass clean. To the upper edges of the vertical mold faces is soldered a horizontal piece of glass to serve as base of the mold when it is removed and inverted. The tops of the finished molds are left free to allow for shrinkage during polymerization. The solder employed is the fusible metal alloy, Belmont No. 255,

applied in a molten state with a soldering iron. It has a melting point (124 C) which is above the temperature maintained during polymerization of the plastics and since it neither contracts nor expands upon solidification, it imparts no strain to the mold walls. It can be removed readily from the glass. The procedure for assembling the molds while on the jigs makes it possible to hold angles within 1.5 min of arc.

FIGURE 6. Rhomb and prism molds ready to receive plastic.

A group of prism molds ready for use is shown in Figure 6. After the prisms have been fabricated, the solder is pried off the mold with a knife, the mold walls are disengaged from the finished prisms, and both solder and glass are ready for use again.

INJECTION OF THE POLYMER

The injection of the partially polymerized material into mold cavities whose edge openings are narrow, such as molds for double-convex lenses, is accomplished through cone funnels prepared by wrapping PVA sheeting around wooden forms and cementing with PVA solution. An amount of 500 to 600 cu cm of material is put into a cone, and the top is folded over so that no air is trapped. The bottom of the cone is snipped off with a pair of scissors and this end is inserted in the opening down to the bottom of the mold cavity. The operator then continues to fold over the top of the cone, squeezing the material into the mold and at the same time retracting the cone. Dust is kept out by surrounding the injection table with acetate sheeting covers.

When the mold cavities have wide edge openings, as molds for prisms and concave lenses, a simple pouring spout is inserted into the 1,000 cu cm flask containing the partial polymer and filling is done by gravity pouring.

Glass tubes permit the material to enter at the top of the mold and flow to the bottom in such a manner as to prevent the entrapment of air.

The prism molds containing styrene are left unsealed during the solidification of the prisms. Those containing CHM are covered with a sheet of cellophane because air inhibits its polymerization.

In sealing lens molds, the flap of tape is pulled down across the opening and sealed with a roller. This procedure extrudes all excess material, and at the same time prevents air from being caught within the mold. Surplus material is then wiped off, and the flap is fastened securely with Scotch or Jonflex tape to prevent sucking in air bubbles when the material shrinks in baking.

With the filled mold assemblies positioned on simple V blocks (V-shaped troughs formed by two flat pieces of wood), the desired thickness of the final lenses can be realized within a tolerance of ± 0.010 in. without further equipment.

Alignment of the mold faces of spherical lenses need not be very accurate, because the lenses are optically centered and trimmed on a lathe. An alignment of from ½ to 2 degrees is maintained, depending on the curvatures and on the diameters of the untrimmed lenses.

For aspherical lenses, on the other hand, molds must be as well aligned as the finished lens is required to be. Where tolerances on wedge or thickness are closer than can be met by the use of wooden V blocks, molds are held in jigs during baking. Tolerances of 0.002 in. in thickness and 0.002 in. in wedge over a 3-in. diameter have been met.

The Baking Cycle

The manufacture of accurate optical elements is completed by placing the molds, filled with partially polymerized material, in constant temperature ovens and baking at two successive temperatures over a period of several hours or days. The material is solidified at the first temperature, and polymerization is brought substantially to completion at the second higher temperature. Both baking temperatures are below the softening point of the polymer. The bake times and temperatures required to complete the finished elements depend on the plastic, the size of the molded elements, and the quantity of polymerization catalyst employed. Table 3 shows typical baking times and temperatures for various optical elements. Polymerization slows down after solidification, and very little takes place in the last few hours of baking. It is important that styrene be as completely polymerized as possible during the final bake in order to prevent crazing.

TABLE 3. Baking times for typical optical elements.

Element	Plastic	Per cent catalyst	Baking cycles I Temp. (C)	I Time (hr)	II Temp. (C)	II Time (hr)
Lens	styrene	1.0	40-70	2-30	83	15-24
Lens	CHM	0.3	25-70	2-24	80	12
Prism	styrene	0.5	40	24-48	80	25-40
Prism (thin)	CHM	0.3	50	2	80	5

During the experimental studies of homogeneity in plastic optical elements the effect of polymerization rates was studied for CHM, methyl methacrylate, allyl methacrylate, methacrylic anhydride, benzyl methacrylate, and styrene. For a given substance, the rate of polymerization was found to depend on catalyst concentration, temperature, pressure, and, with copolymers on composition. Some of these effects are shown graphically for typical plastics in Figures 7 and 8.

Figure 7 shows the polymerization rates measured calorimetrically for two monomers and for a mixture. The increase in polymerization rate when two monomers are mixed is striking. The methacrylic anhydride apparently functions as a detonator in initiating chains. Control of the temperature in such a mixture would be extremely difficult.

Catalyst concentration produces a marked effect on the polymerization rate and hence on the rate at which the liberated heat of polymerization must be dissipated.

The result of autocatalytic heat polymerization due to the poor conduction of heat by the polymer is shown graphically in Figure 8. Measurements were made by thermocouples placed at the center and at the edge of a mass of methyl methacrylate. The region of high

temperature was observed as a small, nearly spherical, "hot spot" of higher refractive index in the center of the mass, rapidly growing until it covered the entire mass. The cooling of the outer portion by a water bath resulted in inhomogeneities which were clearly visible. The rapid changes present at the critical points also lead to bubbles and other evidences of strain.

Removal from the Mold

The molds containing polymerized optical elements are taken from the ovens after final

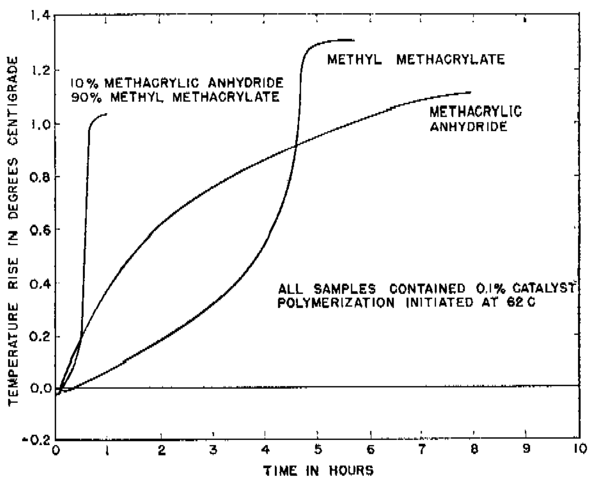


FIGURE 7. Polymerization rates for two monomers and for a mixture.

baking, and the mold walls are removed from the formed elements. Removal is accomplished by stripping the tape from mold edges and immersing the molds in four successive filtered water baths maintained at progressively lower temperatures of 80, 70, 60, and 50 C.

The adhesion of the elements to their molds is usually destroyed before the assemblies leave the first water bath. The assemblies, however, are carried intact through the four step-down baths before elements and molds are actually disengaged from each other. This procedure insures complete disengagement and is believed necessary to prevent cracking of mold and element from thermal shock.

After the assemblies are taken from the last separating bath, the elements are removed from the molds, rinsed in warm water, and blown dry. At this stage, the elements are completed optically. After plastic particles are scraped from old edges, the molds are cleaned with ethyl acetate and lens tissue, polished with ethyl alcohol, and are then ready for re-use.

When prism assemblies are removed from the oven, the metal cement is pried off with a blade and the base of the mold is knocked off. The prism and the mold side walls are then placed in a water bath at 80 C for 10 min. At the end of this time, the mold walls fall off easily. The prisms are blown dry with clean, dry, filtered air at room temperature.

After the elements have been separated from the molds, they are placed in a 60 C oven and baked for 5 days to prevent crazing.

Centering and Trimming

Machining of spherical lenses is accomplished on a lathe. Lenses are centered on a vacuum

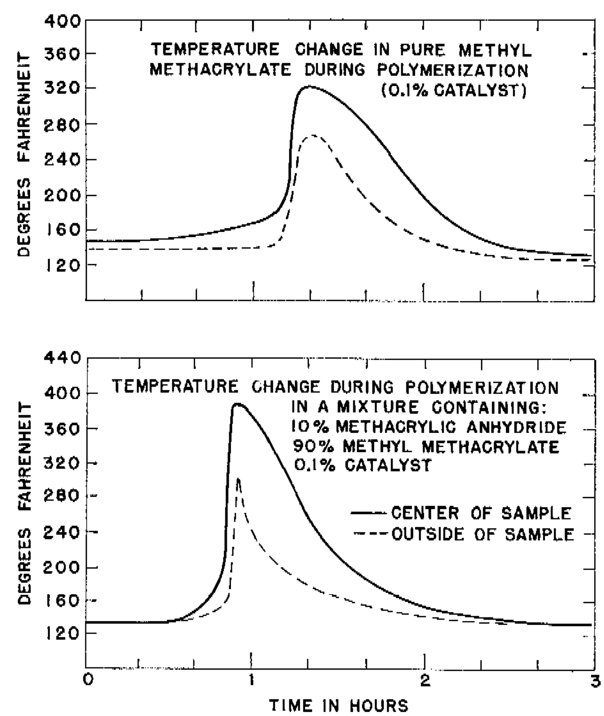


FIGURE 8. Temperature changes during polymerization.

chuck by means of a dial indicator to within ±0.005 in. A perforated sheet of PVA 0.001 in. thick, placed between the chuck and lens, serves to protect the lens face.

Aspherical Schmidt corrector plates, the centers of which are not used optically, are centered

by means of a small circle ($\frac{1}{32}$ to $\frac{1}{16}$ in. diameter) formed from a groove cut in the mold.

With rough cuts of 0.020 in. and finish cuts of 0.002 in., the lenses are turned to the proper diameter by advancing the cutting tool radially (never parallel to axis of rotation) while it is still in contact with the material. Machining of prisms may be done on either a lathe or a shaper.

Yield

In concluding the discussion of manufacturing technique, a few remarks about the percentage yield of elements may be made. The yield varies with the size and shape of the element. For a representative month, out of 421 lenses (2.8-in. diameter) cast, 243 were acceptable, a yield of 58 per cent. The greatest cause of rejection was pullaway from the mold. Bubbles in the element accounted for the next highest rejection factor.

8.4 PHYSICAL PROPERTIES OF CHM AND STYRENE

An evaluation of the optical quality of plastic lenses, prisms, and flats is given in some detail in Section 8.7. In this section a summary of the pertinent physical properties of CHM and styrene is presented.

Index and Dispersion. The refractive indices of three 60-degree styrene prisms and three 60-degree CHM prisms were measured by the National Bureau of Standards. These prisms were measured by the method of minimum deviation, in a stirred air bath on a spectrometer table at controlled air temperatures near 15, 35, and 55 C. All results have been corrected to refer to air at these temperatures and at a pressure of 760 mm of mercury and are given in Table 4.

The indices of Table 4 are the mean values for the three prisms measured. In the case of the styrene prisms, the individual values exhibited a range of 0.00002 to 0.00006, while for the CHM prisms the range was considerably larger, namely 0.00014 to 0.00016. Both ranges refer to the average for the three temperatures involved and for all five wavelengths. The probable error of the experimental determinations is estimated at less than $\pm 1 \times 10^{-5}$, but the systematic errors may be three or four times that amount.

It is necessary for optical designers to know the partial dispersions of the materials with which they are working. These are listed in Table 5. Corresponding reciprocal dispersions (ν-values) are 56.9 and 31.0 for CHM and styrene, respectively.

Table 4. Index of refraction of plastic prisms as a function of temperature and wavelength.

Wavelength (A)		15 C Styrene	15 C CHM	35 C Styrene	35 C CHM	55 C Styrene	55 C CHM
A	7678.58	1.58116	1.50165	1.57853	1.49923	1.57581	1.49640
C	6562.793	1.58696	1.50448	1.58429	1.50208	1.58158	1.49924
D_1	5892.62	1.59232	1.50705	1.58966	1.50464	1.58694	1.50181
F	4861.327	1.60616	1.51343	1.60343	1.51099	1.60063	1.50811
G′	4358.342	1.61760	1.51842	1.61482	1.51596	1.61198	1.51309

Table 5. Partial dispersion of plastic prisms.

Styrene		CHM	
$n_F - n_C$	0.01920	$n_F - n_C$	0.00895
$n_D - n_C$	0.00536	$n_D - n_C$	0.00258
$n_F - n_D$	0.01384	$n_F - n_D$	0.00638

Figure 9 shows the variation of index of refraction measured on 412 styrene prisms representative of the fabrication technique. Although production tolerances have been placed at ± 0.0015, 75 per cent of the plastic elements produced fall within a range of ± 0.0004 on either side of the mean. Sixty-five CHM prisms, measured with the precision refractometer in the same manner as those of styrene, showed a total spread in index values comparable with that for styrene.

The refractive index of plastic elements can be duplicated within production tolerances over

[redacted]

a period of months. Measurements made on styrene polymer taken from production lots over a period of 8 months and on CHM polymer over a period of 5 months indicate an extreme range of 0.0012 in refractive index, the average fluctuation being one-half this amount.

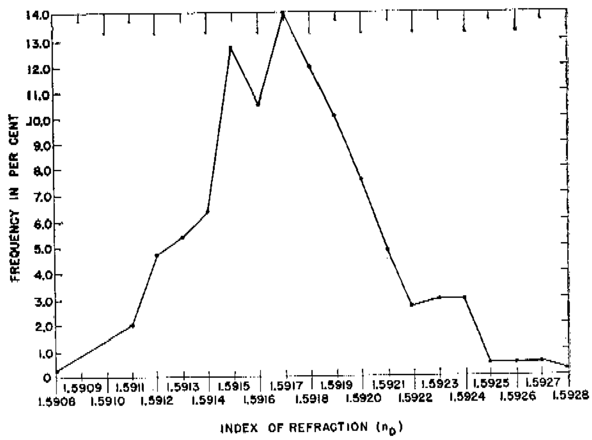


FIGURE 9. Variation of index of refraction in 412 styrene prisms.

The index of both CHM and styrene optical elements undergoes change with time. Index measurements of 7 styrene elements and 6 CHM elements, made at 1-month intervals, indicated decreases on the average of 0.00069 and 0.00052, respectively, over a period of 8 months.

Homogeneity. The internal homogeneity of styrene and CHM optical flats has been tested by double transmission in an interferometer at the Mount Wilson Observatory. The disks used were approximately 1 in. thick and 6 in. in diameter, and were molded between a pair of Pyrex flats.

The surfaces of the disks were first tested for flatness with a test plate. They showed uniform curvatures amounting to between 6 and 20 fringes over a central circle 3¾ in. in diameter. Although one surface was convex and the other concave on each disk, the two curvatures were nearly equal in amount, showing that the disks had warped as a whole while the faces remained nearly parallel. Homogeneity over 3-in. diameter areas at the centers of the disks varied between 1 and 4 fringes for the double transmission with the interferometer. A part of this apparent inhomogeneity might have been due to the observed curvature of the surfaces.

The interferometer test is time-consuming. Direct examination of a sample under the polariscope can often afford a rapid and reliable indication of its homogeneity, especially in the case of styrene, because lack of homogeneity is associated with strain. The amount of retardation present in most cast styrene prisms amounts to about three-quarters of a wave per 1¼ in., over all the area except at the very corners. Resurfaced prisms made from annealed styrene blanks have slightly lower retardations, about one-half wave or less, and variations are uniformly distributed.

Resurfaced prisms, as viewed in the interferometer, appear to have better homogeneity than do those cast in a single operation, and they are nearly strain free. This may indicate that surface strain is largely responsible for whatever inhomogeneity is found in styrene prisms.

Surface Accuracy. Flatness of the surfaces of plastic optical elements is tested with a monochromatic light source against a glass flat. To secure accurate readings, the temperature must be uniform throughout the sample; the ambient temperature must be constant within 0.25 C over relatively long periods of time.

With respect to surface flatness, prisms of CHM are in general less accurate than those of styrene, although of comparable homogeneity. Recent tests of CHM prisms have shown 3 to 4 fringes over an area approximately 1¼ in. square. Styrene prisms, such as those used with the 6x30 binocular, having faces approximately 1 in. square, have proved to be flat within 1 to 3 fringes. Curvature in most cases is concave. A further critical examination of the surface and interior homogeneity of finished optical elements will be given in the last section of this chapter.

Strain. Birefringence in inorganic glasses is always a sign that stress, either external or internal, is present; to obtain the glass in an optically isotropic state, it is only necessary to relieve all the stresses. Organic resins likewise exhibit stress birefringence, but of magnitudes which vary greatly with the nature of the resin,

[redacted]

and, in addition, they have another kind of birefringence which persists in the absence of mechanical stress and which may be called plastic birefringence.

Varying widely, but generally of a higher order of magnitude than stress birefringence, this effect has long been recognized and has lately been put to use in photoelastic studies. It is doubtless of the same nature as the streaming birefringence observed with some liquids (most strongly with solutions of high polymers), and may be ascribed to the orientation of birefringent structural units by viscous flow. Plastic optical parts of CHM and styrene, cast according to current techniques, exhibit birefringences up to 95 and 162 $m\mu$ per cm, respectively. These are believed to result from plastic deformations introduced by the volume contraction on polymerization under conditions of adhesion to rigid mold walls.

Porro prisms of styrene, $^{15}/_{16}$x$1\frac{1}{4}$ in. thick leg, were bound in pairs to form squares and were examined without making optical contact across the air gap. A single examination made through the central area of the prisms showed a birefringence of 130 $m\mu$ per cm.

Both CHM and styrene have positive birefringence in tensile elastic stress and negative birefringence in tensile thermal plastic stretch. A complete analysis would probably show all of the observations to be consistent with a picture of plastic deformation consequent upon volume contraction during polymerization, and adhesion of the cast to the rigid mold walls. Similar birefringences are found in thin sheets of some polymers prepared by casting solutions on glass plates and allowing the volatile solvent to evaporate, the film adhering to the glass during drying.

Hardness. Hardness measurements of styrene and CHM, as well as of allyl methacrylate, EDM, and Lucite, were made on a Rockwell hardness tester with a $\frac{1}{8}$-in. ball, a 20-kg major load, and a 10-kg minor load. This modification of the usual Rockwell hardness test was made because the 60-kg major load ordinarily used always cracked CHM samples and usually cracked those made of styrene, owing to the short average chain length of the polymers and their consequent brittleness.

Tests with this modified instrument can be made rapidly and, on the whole, results obtained from various runs are consistent. While not quantitative as measured on the Rockwell Z scale, the results are clearly indicative of the relative hardness of the materials measured, as follows:

Polymer	Hardness
styrene	103-105
CHM	107-109
allyl methacrylate	124-125
EDM	126
Lucite	99-100

Density. Optical plastics are from one-third to one-half as heavy as inorganic glasses of corresponding optical characteristics. The density of CHM is 1.0951 g per cu cm; the density of styrene is 1.0493 g per cu cm.

Water Absorption. CHM and styrene differ strikingly in water-absorption characteristics from plastics heretofore proposed for optical applications. Under ordinary conditions, so little water vapor is absorbed that it has no measurable effect on optical performance.

Elements of both CHM and styrene have been desiccated for 24 hr in an atmospheric desiccator filled with calcium chloride, after which the elements were boiled in water for 1 hr. This extreme test showed water absorption of 0.121 per cent for CHM and 0.087 per cent for styrene, with index changes of −0.00244 and −0.00058 respectively. A test made under the same conditions on Lucite (methyl methacrylate) showed water absorption of 0.801 per cent with an index change of −0.00176.

Although the index change shown for CHM would affect the focus of a simple lens by approximately 1 per cent, it is apparent that the index change under normal conditions would be negligible.

Transmission. The transmission of both CHM and styrene is approximately 90 per cent, uncorrected for reflection, over that region of the spectrum from 10,000 A to 3,900 A for a path length of 1 cm. CHM is almost invariably water white. There is a slight yellow tinge in styrene at times, caused by the catalyst used during polymerization.

Transmission curves for CHM and styrene are shown in Figure 10. The measures are uncorrected for surface losses.

Softening Temperatures. The temperatures at which the various plastic materials soften depend on such factors as the catalyst used and the degree of polymerization attained. However, the following data are indicative of the softening-point temperatures of styrene and CHM.

Polymer	Softening Point Degrees Centigrade
styrene made with 0.25 per cent acetyl benzoyl peroxide	82-83
styrene made with 1 per cent benzoyl peroxide	about 78
CHM partially polymerized by boiling	61-62
CHM partially polymerized at 95 degrees	67-71

The temperatures given above are those at which the samples sagged not more than

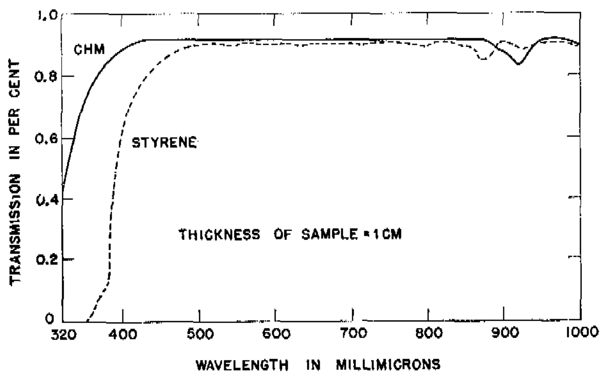


FIGURE 10. Spectral transmission of CHM and styrene.

0.0005-in. after 14 to 16 hr when tested in the following way:

Flat strips, 3x⅛x½ in., of the materials to be tested were placed with their ends on shoulders. Steel balls, ½ in. in diameter, fixed in place by guides, were placed on the upper surfaces of the flats. Several samples of the same material were heated for about 15 hr at different temperatures and the sag was then measured with a dial indicator. The softening temperature was taken to be that at which a sample sagged not more than 0.0005 in. in the time interval stated.

Thermal Expansion. Organic resins have undesirable thermal properties. The high coefficient of thermal expansion of both CHM and styrene leads to many problems in the design of optical instruments, chiefly in the manner of mounting the plastic elements.

The coefficient of linear expansion of CHM is 76×10^{-6} per degree centigrade. The coefficient of linear expansion of styrene is 71×10^{-6}. In comparison, that for glass is of the order of 9×10^{-6}.

The thermal index coefficient for both materials has been calculated from National Bureau of Standards measurements. The mean change in index per degree centigrade rise in temperature, based on the index change from 15 to 55 degrees is:

styrene	—0.000136 at the sodium D line
CHM	—0.000131 at the sodium D line

Thermal Conductivity. Samples of CHM and styrene were tested on a special thermal transmission tester. The thickness of the sample was 0.25-in. and the mean temperature of the sample was 70 F. The resulting thermal conductivities were:

Styrene:
0.64 Btu per hr per sq ft per degrees Fahrenheit per in.
2.21×10^{-4} calorie per sec per sq cm per degrees centigrade per cm

CHM:
0.67 Btu per hr per sq ft per degrees Fahrenheit per in.
2.31×10^{-4} calorie per sec per sq cm per degrees centigrade per cm

Scratch Resistance. On the Mohs scale of hardness both CHM and styrene are between 2

TABLE 6. Tensile, impact, and flexural strength of CHM and styrene.

	CHM	Styrene
Tensile strength (psi)	1255	1980
Impact (ft-lb per in. of notch)	0.14	0.24
Flexural (psi)	2280	3850

and 3. This means that both materials are scratched by calcite and all harder materials, but not by talc and gypsum and materials with corresponding abrasive qualities.

Tensile, Impact, and Flexural Strength. Five samples each of CHM and styrene were examined for tensile strength, for impact strength in accordance with ASTM Standard D256-43, and for flexural strength in accordance with ASTM Standard D650-42T. The results are shown in Table 6.

8.5 PLASTIC OPTICAL SYSTEMS

8.5.1 Optical Characteristics of Plastic Systems

A number of optical instruments have been designed and constructed to explore the utility of plastic elements. Representative of these instruments are the seven whose characteristics are listed in Tables 7a and 7b. Optical proper-

TABLE 7a. Calculated performance of optical systems.

	T-108 antitank telescope	T-118 antitank telescope	6x40 inverting telescope
Magnification	3×	5×	6×
Exit pupil	1 in.	0.8 in.	0.3 in.
Field of view	6°	6°	10°
Eye relief	6½ in.	4 11/32 in.	⅝ in.
Spherical aberration	10 sec	8 sec	12 sec
Curvature of field (objective only)	0.09 diopter 5 in. radius	0.18 diopter 6½ in. radius	3.5 diopter 3 in. radius
Coma	20 sec	16 sec	24 sec
Distortion	0	0	slight barrel distortion*
Axial color	7 sec	6 sec	6 sec
Resolving power	5 sec at c.o.f.† 20 sec at e.o.f.‡	5 sec at c.o.f. 20 sec at c.o.f.	5 sec at c.o.f.
Equivalent focal length of objective	381.0 mm	507.2 mm	240 mm
Transmission	31%	35%	60%
Clear aperture	75 mm	100 mm	40 mm
Astigmatism	less than ½ diopter	less than ½ diopter	½ diopter

* Not computed.
† Center of field.
‡ Edge of field.

TABLE 7b. Calculated performance of optical systems.

	$f/0.7$ Schmidt system	$f/2.8$ Aerial camera lens	$f/1.6$ Reflex sight	Offset wedge Mark 7
Magnification, permissible	...	...	...	7×
Field of view	28°	47°	12°	7°
Spherical aberration	10 sec	50 sec	1 min	...
Curvature of field	2¾ in. radius	flat	1½ in. radius	...
Coma	*	8 sec	1½ min	...
Distortion	0	0.36% at 19½° 0 at 23½°	*	...
Axial color	none	8 sec	45 sec	...
Resolving power	1 min at c.o.f.†	30 lines per mm	1½ min	8 sec
Equivalent focal length	2⅜ in.	7.38 in.	5⅝ in.	...
f-number	$f/0.6$	$f/2.8$	$f/1.6$	...
Transmission	82%	81%	90%	92%
Clear aperture	3⅛ in.	2⅔ in.	3½ in.	2 in.
Back focal length	...	2.3 in.	...	...

* Not computed.
† Center of field.

[redacted]

ties of three low-power telescopes are given in Table 7a, while Table 7b presents data for more specialized visual and photographic systems.

In order to interpret the table, the following definitions or usages must be borne in mind:

1. Spherical aberration: The angle subtended at the second principal point of the objective lens by the diameter of the circle of confusion containing at least 75 per cent of the light.

FIGURE 11. T-108, 3x75 telescope for antitank guns.

2. Curvature of field: The figures in Table 7a represent the diopter differences in focus between the center and full field of the objective.

3. Coma: The angle subtended at the second principal point of the lens by a circle of such diameter that it includes 70 per cent of the light in the comatic image.

4. Axial color: The angle subtended by the diameter of the circle of confusion which includes the F, C, and D rays. (F and C as a rule are coincident).

5. Astigmatism: Given in diopters at the edge of the field.

6. Resolving power: The angle subtended by adjacent discernible lines on a U. S. Bureau of Standards resolving-power chart when viewed through the instrument.

7. Distortion: Expressed in terms of percentage of linear distance from the center of the field for the stated field angle.

The T-108 telescope shown in Figure 11 is a 3× direct-sighting telescope for use on antitank guns. The unusual features of the instrument are its large eye relief (6.5 in.) and its large exit pupil (1 in.). A cast mirror-erecting system includes a reticle. By the use of a combination of glass and plastic elements in the objective the change of focal length with temperature has been kept as small as possible. The optical design is shown in Figure 12. Specifications and details of the T-108, of which 1,178 were manufactured, are given elsewhere.[6d]

Optical tests of a typical T-108 telescope showed the resolving power to be 3 sec at center of field, 7 sec at half field, and 45 sec at the edge of the field. Tests with a dioptometer of $11\frac{1}{2}$-in. focal length indicated negligible field curvature and longitudinal chromatism. Parallax, with the aperture stopped to 1.5 cm was undetectable with 30× magnification both at half and at full field.

The T-118 telescope is very similar in design and performance to the T-108 but has a larger aperture and higher power.

The 6x40 telescope is an inverting instrument designed primarily for testing the performance of a plastic optical system against a corresponding glass system (the Mark 15 gunsight). Such a comparison for the T-108 telescope is described in Section 8.7.1.

In the Mark 7 offset wedge attachment for binoculars, illustrated in Figure 13, a double image is obtained by means of holes through which a direct image of an object is superposed on a deviated image produced by the prism. The optical design of the prism system is shown in Figure 14. The wedges resolve 7 to 10 sec throughout the entire field. Longitudinal chromatism is too small to be measured.

An aerial camera lens design (focal length 7.38 in., $f/2.8$) is shown in Figure 15. The effects of temperature change on the focal length have been minimized by inserting a glass element *(D)* in the system.

The $f/1.6$ reflector sight was designed for fixed gunnery in aircraft. It consists of a folded optical system with a spherical reticle. Over the entire field, the reticle rings are fixed in direction in space within $\frac{1}{3}$ mil.

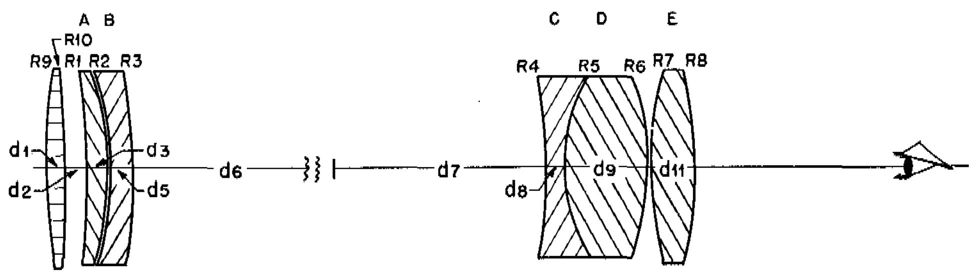
The small, fast Schmidt system ($f/0.7$) is composed of the usual spherical reflecting mirror and a correcting lens mounted in a plastic tube which affords temperature compensation for the optical parts. At the center of the field

80 per cent of the light is concentrated in a 50-μ circle. Production instruments (some 5,000 have been made) resolve clearly 3 min of arc at the center of the field and 6 min at the edge over the entire temperature range, —40 C to 55 C. Figure 16 shows the optical design.

8.5.2 Other Instruments Designed

In addition to the representative instruments described above, numerous others have been designed and some of these constructed. Their diversity is shown by the following list:

Galilean binoculars, 3x60 and 5x80
$f/1.9$ illuminated sight collimator



n_D = 1.523, ν = 58
n_D = 1.5915
n_D = 1.5062

FIELD = 6°
EXIT PUPIL = 1"
EYE DISTANCE = $6\frac{1}{2}$"

OBJECTIVE EFL = 15.033" 381.84 MM
EYEPIECE EFL = 4.86" 123.65 MM

	LENS DIA IN INCHES		MM	INCHES		MM	INCHES
GLASS LENS	3.125	R9	273.92	10.433	d1	8.25	0.325
		R10	706.70	27.822	d2	6.75	0.266
A	3.000	R1	706.7	27.82	d3	10.125	0.399
B	3.000	R2	124.7	4.909	d4	0.13	0.005
C	2.843	R3	424.0	16.693	d5	7.5	0.295
D	2.843	R4	223.2	8.787	d6	363.137	14.297
E	3.000	R5	70.7	2.783	d7	84.61	3.331
		R6	103.4	4.070	d8	7.33	0.289
		R7	146.2	5.765	d9	33.33	1.312
		R8	192.7	7.586	d10	0.19	0.007
					d11	17.33	0.682

LENS DIA TOLERANCE +.000" −.003" (lenses A–E)

FIGURE 12. Optical design for T-108 telescope.

$f/2.5$ anastigmat lens with field flattener, focal length 7 in.
standard 6x30 binocular
7x50 prism binocular
140-mil reflecting offset, Mark 8
$f/3$ aerial camera lens
3x75 prism telescope
$f/0.7$ camera lens
$f/0.7$ parabolic reflector, focal length 1 in.
3x75 prism telescope

8.5.3 Athermalization

One of the principal considerations in the design of plastic optical instruments is the elimination of changes in focal length due to temperature fluctuations. Refocusing the instrument to offset changes in focal length is obviously inconvenient and in many cases impractical. An instrument designed to minimize these temperature effects is said to be *athermalized.*

Athermalization can be accomplished for a plastic lens system by the addition of one or more glass lenses; these have a negligibly low coefficient of thermal expansion and their optical properties are substantially unaffected by changes in temperature. The glass element in the T-108 telescope, for example, decreases the temperature effects and at the same time protects the plastic lens elements against scratching. However, freedom from change in focal length can be realized, even in athermalized systems, only when all elements are in thermal equilibrium.

It is also possible to athermalize a plastic lens system by the use of a housing composed

of alternate layers of metal and plastic. The effect of a cumulative contraction adequately compensates for change in the optical elements. This procedure does not appear to be practical, however, because of the large number of layers required—four plastic and three metal—if the composite housing extends all the way from the lens to the focal surface.

Partial athermalization for focal distance can be attained quite simply by using an aluminum housing.

A plastic mirror system may be completely athermalized by making the connection be-

FIGURE 13. Mark 7 offset wedge for binoculars.

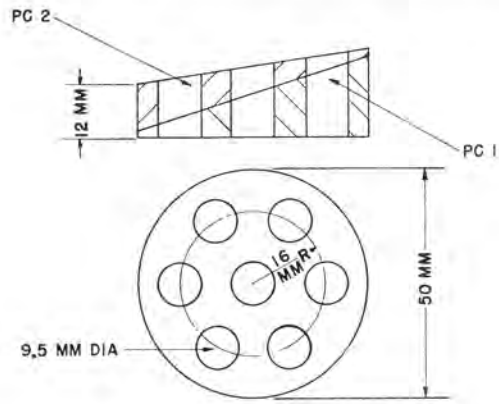
tween the mirrors, and from the mirror to the focal surface, of the same plastic material as the mirror. This is also essentially true in such a system as the Schmidt, in which the refracting element has negligible power.

The relatively large coefficient of thermal expansion of plastics (about 71×10^{-6} per degree centigrade for styrene, and 76×10^{-6} per degree centigrade for CHM) necessitates certain precautions in mounting which are not necessary for glass elements.

Plastic lenses are usually mounted in a material of approximately the same coefficient of expansion. If this procedure is followed, any of the commonly accepted techniques for mounting glass lens components can be used with plastic lenses: snap rings, threaded retaining rings, push fit rings, and so forth. Lenses have also been cemented to plastic sleeves with a special cement which forms a bond between the housing material and the optical material without injury to the plastic elements.

It may be necessary to center the plastic sleeve containing the lenses in a metal tube, as was done in the T-108 and T-118 telescopes, and in the $f/2.8$ camera. In such cases, the radial expansion of the sleeve may conveniently be taken up with an elastic material, such as the rubber rods used as bushings in the $f/2.8$ camera lens mount. For the accurate centering necessary in boresighted instruments, the plastic sleeve may be made to ride on a conically machined metal outer sleeve. This was done in the T-108 and T-118 telescopes.

In some instances it may be desirable to mount the lenses directly in an outer housing made of a material with a considerably lower thermal coefficient than the lenses. This is perfectly feasible wherever the centering tolerance



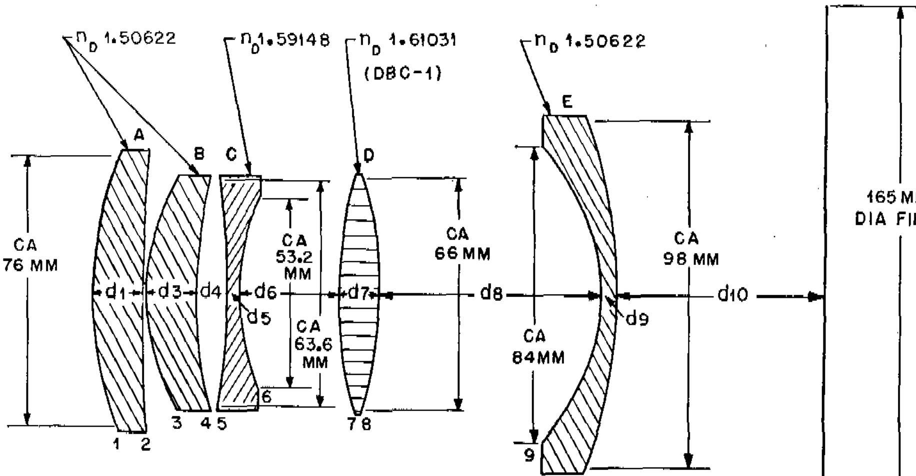
	MM	MM	
WEDGE	PRISM ANGLE	n_D	ν
PC I	17°-20'-19"	1.5060	57.5
PC 2	8°-4'-30"	1.5911	31.5

FIGURE 14. Optical design of offset wedge attachment.

of the lenses is large enough to permit the clearance necessary for the full range of temperature to be encountered in use. Under these conditions, thermal compensation can be achieved by the use of metal springs, rubber bushings, gaskets, and other compression devices placed directly between the lenses and the housing.

Rapid changes in temperature injure the re-

[redacted]



TOLERANCE			MM	INCHES		MM	INCHES
CA1	±0.1	R1	$105.97^{\pm 0.23}$	4.173	d1	14.50	0.571
CA2	±0.5	R2	$537.22^{\pm 4.40}$	21.151	d2	0.29	0.012
CA3	±0.1	R3	$65.38^{\pm 0.09}$	2.574	d3	14.50	0.571
CA4	±0.5	R4	$127.40^{\pm 0.40}$	5.016	d4	8.56	0.337
CA5	±0.5	R5	$237.59^{\pm 0.90}$	9.354	d5	3.48	0.137
CA6	$^{+0.5}_{-0}$	R6	$65.38^{\pm 0.09}$	2.574	d6	28.62	1.127
CA7	$^{+1}_{-0}$	R7	$124.81^{\pm 0.26}$	4.914	d7	11.80	0.464
CA8		R8	$118.40^{\pm 0.18}$	4.662	d8	64.79	2.551
CA9	±0.3	R9	$60.19^{\pm 0.11}$	2.370	d9	4.45	0.175
CA10	± 1	R10	$145.30^{\pm 0.53}$	5.721	d10	59.30	2.335

	INCHES
A	$3.117^{+.000}_{-.003}$
B	$2.629^{+.000}_{-.003}$
C	$2.629^{+.000}_{-.003}$
D	$2.723^{+.000}_{-.004}$
E	$3.978^{+.000}_{-.003}$

47° FIELD
190.5 MM = E F L

FIGURE 15. Optical design of $f/2.8$ aerial camera lens.

solving power of plastic lens systems more than they do a glass system. Therefore, where the system is subject to such changes, it is necessary to insulate thick massive plastic lenses from the outer walls of a metal housing. This may be done by mounting the lenses in a plastic sleeve which bears upon the metal outer housing at two narrow bands. The dead air space thus formed provides adequate insulation. This construction was used in the $f/1.6$ sight.

8.5.4 Current Limitations

In concluding the discussion of instrument and design characteristics, it may be well to summarize the limitations imposed on the optical designer by the use of the two available plastics (CHM and styrene). Design possibilities with all plastic elements and with plastic elements combined with glass have been more fully discussed elsewhere.[b] There are four limitations:

[b] See Chapter 1 and Section 10.7 of this volume and reference 6 of Chapter 8.

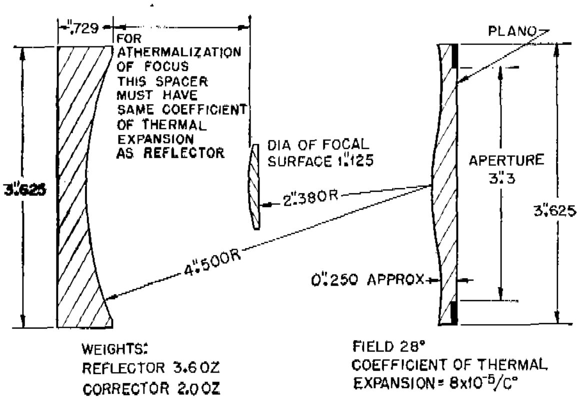


FIGURE 16. Optical design of $f/0.7$ Schmidt system.

1. The first arises from the high coefficient of thermal expansion, in each case nearly 10 times that of glass. A small change in focal length caused by a change in temperature may be corrected in a focusing instrument or automatically compensated in an athermalized instrument. However, the rate at which the plastic elements will come to equilibrium may still

[redacted]

present a serious problem since the high specific heat and low heat conductivity of plastics combine to encourage steep temperature gradients within the optical elements with a corresponding reduction in performance.

2. The low scratch resistance of the plastics now in production is another limiting factor, for most plastic optical systems have had to be protected by flat glass windows.

3. While CHM and styrene are vastly more homogeneous than other synthetic resins hitherto developed, they are not as homogeneous and haze-free as the best glass elements, nor do they have the same surface accuracy. For these reasons the optical designer must restrict himself to instruments of 3 to 5 power, in which slight inhomogeneity and departure from perfect figure do not have serious consequences.

4. Although optical constants of CHM and styrene produce some advantages, no known plastic combination is as advantageous for certain types of camera lenses as some of the new high-index high-ν crown glasses. A plastic of sufficiently high index and high ν-value and a plastic of sufficiently low ν-value are still much to be desired.

tered light produced by scratches. In telescope systems, this exposure may be avoided to a great extent by making the leading element of glass, which serves as a protective surface in addition to helping stabilize the system thermally. But in other cases a protective window is usually required which may interfere with the optical performance of the instrument. This objectionable feature in plastic optical elements may be minimized either by the synthesis of a plastic which is inherently hard or by the addition of a coating which hardens the surface of the ordinary plastic.

Cross-linked polymers, such as ethylene dimethacrylate and allyl methacrylate, have shown some promise of being the answer to the demand for an intrinsically harder plastic.[6e] These are 25 per cent harder on the Rockwell test than either CHM or styrene. But they have a tendency to craze and to be highly water absorbent, and hence a considerable amount of research on their synthesis and fabrication will be required to make them acceptable.

The application of surface coatings to ordinary plastics to make them abrasion resistant has been more successful. Two principal methods will be described: (1) the evaporation of a

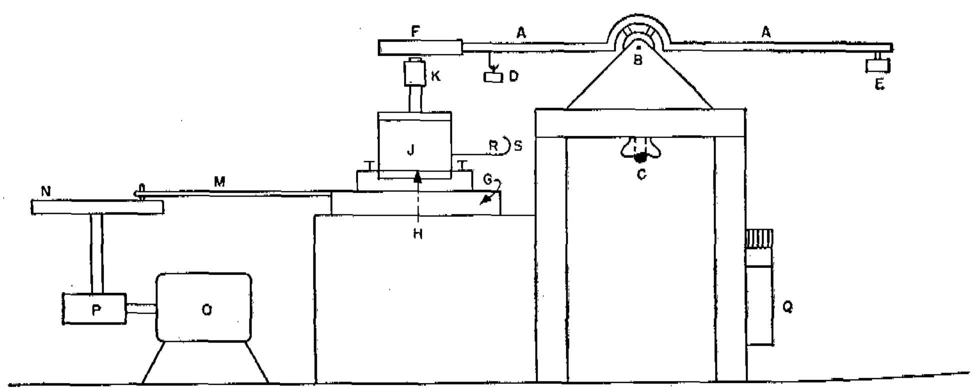


FIGURE 17. The abrader, used in testing the resistance of a surface to abrasion.

8.6 SURFACE-HARDENING COATINGS FOR OPTICAL PLASTICS

The principal objection to the extensive use of plastic elements in optical systems is the low scratch resistance of the material. Where the optical surface is exposed to dust, it rapidly deteriorates in efficiency due to increased scat-

coating by the techniques used in deposting metallic films, and (2) exposure to silicon tetrachloride vapor in the presence of ozone.

8.6.1 Evaporation Process

The evaporation technique used at the Polaroid Corporation[6f] is the same as that custom-

[redacted]

arily employed in depositing metal films on plastic elements. The deposition is made at pressures of the order of 5×10^{-5} mm of mercury. Tantulum filaments or boats are used to heat the material.

Twenty-three materials were tried in the evaporation process. These were selected for adequate hardness, low solubility in water, good adhesive powers, index of refraction lower than that of the plastic, and a thermal coefficient of expansion such that the coating would not be likely to crack when subjected to large temperature changes. A few high-index materials were also tried. The films were deposited on styrene flats, and the coating hardness was estimated semiquantitatively by rubbing the surface with a cloth. The estimates of the scratchability of the surface were then correlated with the haze index, as determined in the standard ASTM falling silicon carbide test for mar resistance, D673-42T.

Of the 23 materials tested, only grossularite $[Ca_3Al_2(SiO_4)_3]$ and phenacite $(2BeO{\cdot}SiO_2)$ produced a satisfactorily adhesive coat with hard surface (haze index, 0 to 20). Some others, such as calcium triorthophosphate and calcium silicate, were hard and adhered to the surface, but turned dark in the evaporation process.

Grossularite, in addition to being easily procurable, shows less tendency to crystallize than does phenacite. Phenacite is scarce and expensive, but shows an extremely low haze index on both CHM and styrene surfaces.

It is evident that considerably more experimentation will be required before the evaporation technique can be considered wholly successful in producing hard surface coatings. It is, however, definitely promising.

8.6.2 Silicon Tetrachloride—Ozone Process

Progress in vaporization of surface-hardening materials on plastics, notably Lucite, has been made at the California Institute of Technology under OSRD Contract OEMsr 657.[7] In brief, the procedure consists of exposing the plastic surface alternately to air of controlled humidity and to a mixture of silicon tetrachloride vapor and ozone. Two exposures to the mixture containing silicon tetrachloride are sufficient to coat a plastic. It will resist abrasion by normal cleaning 20 or 30 times as long as will the untreated plastic. A more detailed description of the process, and of the tests devised to measure quantitatively the abrasion of the surface, follows. A knowledge of testing methods is necessary for an evaluation of the success of this hardening technique.

Methods of Testing

In order to measure quantitatively the resistance of a surface to abrasion, a standard test has been developed by which plastics may be compared. The common tests for hardness, such as the Brinell test or the Rockwell test, do not suffice, since they measure body hardness. The Mohs mineral test is not sufficiently refined for the present purpose.

The method of testing which was finally developed consists in drawing back and forth over the surface a pad impregnated with abrasive and in measuring the resulting wear by means of light scattered from the surface. Two devices were developed for this purpose, an abrader and a reflectometer.

The Abrader. Figure 17 shows the abrader in schematic form. It consists of a beam assembly 40 cm long, to one end of which (at F) is fastened the sample plastic to be abraded. Weights may be hung at D to press the sample against the pad holder K with any desired force. A stage G sliding in two runners parallel to the beam is oscillated back and forth by a motor-driven eccentric N. Mounted on the stage is a motor J with vertical shaft which rotates the pad holder at 60 rpm. The stage oscillates with an amplitude of ½-in. approximately 25 times per minute. A counter is attached to the motor which drives the stage, so that the number of strokes of the latter may be recorded. Samples varying in width from ¾ to 1½-in., in length from ⅜-in. to several inches, and in thickness up to ³⁄₁₆-in., may be clamped in the carrier F and abraded.

Two pads are used for the testing. One, called the 20-45 pad, is compounded of 40 per cent rubber, 45 per cent fine silicon (20 to 45 μ diameter), 10 per cent whiting, and small

percentages of accelerator, stabilizer, and stearic acid. The other pad, called the CS-15 pad, is cut from a rubber abrasive disk labeled "CS 15" which is used in the Taber abraser.[c] Before each test the pad must be dressed by allowing it to run for 50 to 100 c over silicon carbide paper. The choice of pad to be used depends on the hardness of the sample to be tested.

In the operation of the device, the sample is placed in clamp *F*, the height of pad is adjusted so that a level shows the sample to be horizontal, and the counterweight *E* is adjusted to balance the beam. Then a 50-g weight is added at *D*, the motors are turned on and the stage allowed to make 100 c. For samples much softer than Lucite, fewer cycles and less weight are used. After the abrasion, the sample is washed to remove any rubber and abrasive. The mark made by the pad is ¾ in. long and ¼ in. wide, and is composed of numerous faint scratches, roughly circular at the ends but having a uniform diagonal pattern in the center. The abrasion is measured in this uniform middle area.

The Reflectometer. Figure 18 shows the optical system of the reflectometer used to measure the abrasion of a sample. Light from the 100-w Mazda projection lamp *S* is focused on the abraded area *P* of the sample at an angle of 45 degrees. A knife edge *E* cuts off unwanted light reflected from the upper surface of the plate. Light reflected from the lower face of the sample is collected by the Weston photronic cell at *C*. A high-sensitivity galvanometer, connected in series with the cell and associated resistors, is used for the measurement.

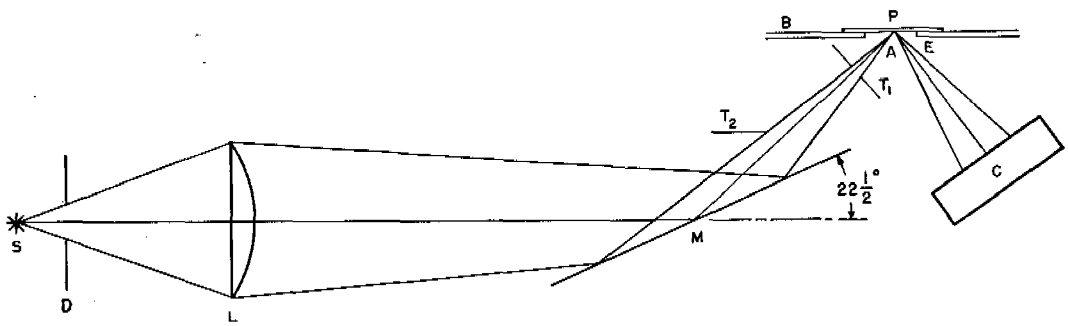


FIGURE 18. Optical system of reflectometer.

The lens, mirror, and shields are adjusted until an image ⅛ in. wide falls upon the sample. Then a slide of Lucite, ⅛ in. thick, is placed over the aperture and the knife edge is adjusted until the beam reflected from the upper surface of the slide is intercepted. Thus for samples thicker than ⅛ in. only light reflected from the lower surface enters the photocell. The area of sample measured is about ⅛ in. square. Once the optical system was adjusted it was never changed. With this restriction, fluctuations due to area of illuminated spot, intensity of the light, etc., were considered to be negligible. When a treated plastic was tested, all measures were referred to an untreated and unmarred sample of that plastic, that is, the reflectometer was set to read zero by proper adjustment of a balancing resistance in the photocell circuit when the untreated plastic was placed over the aperture prior to each measurement of a treated plastic.

In order to measure abrasion, the sample is placed over the aperture so that light falls on an unabraded area and a galvanometer reading is taken. Then an area abraded on one side is measured. The difference in galvanometer reading between measures on abraded area and average unabraded area constitutes the reflectometer measure. These usually range from 0 to 5 for the abrasions customarily measured. The results are precise to about 0.1 unit on this scale, unless the surface is unusually irregular.

If the sample is so warped that it will not lie flat on the stage of the reflectometer, or if it has a mottled or flawed surface, no reliable

[c] Manufactured by the Taber Abraser Corporation, North Tonawanda, New York.

[redacted]

measures can be made with the instrument. At times, when a plastic is coated with a relatively thick film, there is an anomalous reflection effect which invalidates the measures. In these instances the abrasion is determined by comparing the abraded area, obliquely illuminated under a 50× microscope, with an area of known amount of abrasion.

Measures repeated for several months on Lucite with the 20-45 pad, weighted at 50 g and used at 100 c, yielded reflectometer readings with a range 3.0 to 3.7. Since these figures include fluctuations of hardness in the samples as well as fluctuations in the abrasive power of the pad, they furnish an overall measure of the reliability of the test. Similar runs with the CS-15 pad on Columbia Resin 39 gave a constant abrasion of 0.7 to 0.8.

A scale of surface hardness based on the reflectometer measures uses the hardness of Lucite as a unit. The term *abrasion number* [AN] designates the amount of abrasion referred to Lucite (AN = 1). The hardness of Columbia Resin 39 is AN 15. The abrasive powers of the coarse and fine pads were determined empirically by noting the abrasion each produced on a surface of AN 6. Under similar conditions, the coarse pad produces 3.0 to 3.5 times as much abrasion as the fine pad. Formulas for the calculation of AN have been developed for Lucite; other plastics are then referred to this standard.[7a]

TABLE 8. Surface hardness of plastics, determined by abrasion test.

Plastic	Abrader pad	Number of cycles	Abrasion number untreated	Abrasion number treated
Lucite	20-45	100	1.0	15-20
CHM	20-45	50	0.7	10-14
Styrene	20-45	10	0.1	1-3
Bakelite	20-45	50	0.9	...
CR 39	CS 15	100	15	...
Du Pont hardened Lucite	CS 15	100	16-20	...
EDM-CHM	...	...	6-9	...
EDM	CS 15	...	20	...

The results of abrasion tests on samples of Lucite and other plastics are shown in Table 8.

Other Methods for Testing. Other tests[7b] were used for measuring the correlation between actual wear on a plastic surface, due to rubbing with cloth and to weathering, and the abrasion number of the plastic. Another unit of measure, the *scatter number* [SN], was devised to measure the wear effect. A *wear ratio,* defined as the ratio of the number of wipings a treated slide must receive to the number an untreated slide must receive so that both slides give the same SN number, gives a practical measure of the superior hardness of a treated surface.

In the case of untreated CHM and styrene, the wear ratio is approximately the same as the AN (compared to Lucite). Hence the abrasion test is a close measure of the resistance to actual wear. For plastics with hardened surfaces, the wear ratio was always greater than the hardness given by AN; the abrasion test in these instances gives a conservative measure of the resistance to wear. The SN might be used as a criterion in deciding whether a surface is sufficiently free from blemishes to be useful in optical work. Unmarred, untreated Lucite has SN equal to 7. For an excessively marred surface SN exceeds 16. A treated plastic, to be of value, should have an SN of about 11 or less.

Crazing due to temperature fluctuations is a serious defect in hardened surfaces on plastics, and a method for measuring this effect has been developed. When applied to Lucite, it was found that craze lines did not develop on the untreated plastic. For films with a hardness less than 12 AN, crazing usually did not take place. For hardness greater than this value, the crazing increased with the hardness of the film.

METHOD OF OBTAINING HARD FILMS WITH SILICON TETRACHLORIDE

Research in the production of hard surface coatings on plastics was directed toward the application of films of silicon compounds, magnesium fluoride, and aluminum oxide. Wherever possible, both liquid and vapor phase treatments have been attempted. Results of experiments with aluminum oxide films were not successful. The surfaces were not hardened appreciably and in some cases were attacked by the liquids or vapors used. It was possible to

obtain a film of magnesium fluoride on Lucite, but the adherence to the surface of the plastic was poor and no increase of hardness was observed. Furthermore the Lucite softens and becomes flexible in an atmosphere of HF_2 and can be deformed easily. After standing in air for several hours, it becomes rigid but retains its deformed shape. Details of these experiments are given elsewhere.[7c]

Considerable success was achieved, however, with silicon tetrachloride vapor combined with either ozone or nitrogen dioxide. The former combination should lead to a suitable industrial

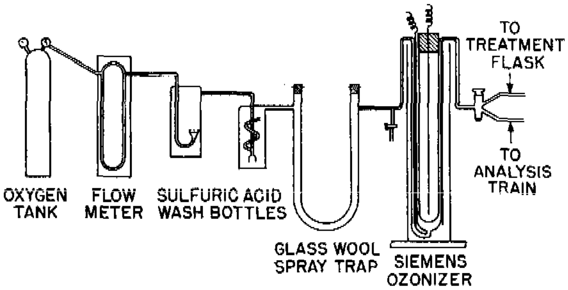


FIGURE 19. Schematic diagram of the ozone train used in the $SiCl_4$—ozone process.

process for hardening plastics. The method has been applied successfully to Lucite and with moderate success to CHM and styrene.

Silicon-Tetrachloride—Ozone Process. To remove adhesive or grease, the plastic to be coated is cleaned in an organic solvent, such as 95 per cent ethyl alcohol. Gentle rubbing with absorbent cotton is permitted, and excess solvent is blotted off with clean cotton towels.

The surface is not wet by water, so it is washed in a thick lather made of Dreft and water which does wet the surface. It is finally rinsed with distilled water until the Dreft is completely removed.

The clean sample is next suspended by glass hooks or Lucite strips in a specially constructed humidifier,[7d] where it is exposed to air of controlled humidity for a length of time dependent upon the relative humidity, in order to condition it for treatment. If the relative humidity [RH] is 75 per cent, the conditioning is continued for at least 30 hr; at RH of 50 to 60 per cent the conditioning requires at least 65 hr. Experiments have shown that if RH is less than 50 per cent, the plastic will not be hardened appreciably; if RH is above 85 per cent the films have a tendency to chip off or to be cloudy. For small objects, it is desirable to maintain RH near the lower end of the range to insure an even film thickness. The recommended RH for large objects is also between 50 and 60 per cent, although higher values yield equally good films.

After the humidifier conditioning, the sample is transferred as quickly as possible to a treatment vessel, and the latter is evacuated to a pressure of 25 to 35 mm of Hg. These treatment vessels are either standard three-neck taper flasks or, for the larger samples, a 10-in. vacuum desiccator. It is preferable to use a water aspirator rather than a vacuum pump because of the injurious action of silicon tetrachloride ($SiCl_4$) vapor on the latter.

Recently distilled $SiCl_4$, in a concentration 0.8 ml per liter, is admitted to the treatment vessel through an evaporator, and the vessel is connected to a standard Siemens laboratory ozonizer, activated by a 15,000 v, 30 ma transformer. A diagram of the ozone train is shown in Figure 19. After running for 20 min, the ozonizer will yield 3.5 to 5 per cent ozone at a rate of 0.2 l per min. The ozone-oxygen mixture is allowed to flow into the treatment vessel at this rate until the pressure is atmospheric. The sample is then exposed to the ozone—$SiCl_4$ mixture for about 2 hr.

Neither the concentration of $SiCl_4$ nor that of ozone is critical. It has been found, however, that concentrations of $SiCl_4$ less than 0.5 ml per liter produce no hardening of the plastic surface.

At the end of the exposure period, the vessel is partially evacuated (3 to 5 min with a water aspirator) and air, which has been dried by passage through a large column of calcium chloride, is admitted through the evaporator. Then the sample is transferred to the humidifier and conditioned for 2 hr more. It is not necessary that this second conditioning be at the same RH as the first, but for large samples, it is recommended that the same RH (50 to 60 per cent) be used in both instances. For small samples, the second conditioning may be carried on at a higher RH than the first, say at 75 per cent.

[redacted]

Again, the sample is transferred to the treatment vessel and exposed to $SiCl_4$ and ozone for a period of ½ to 2 hr. A full 2-hr period is recommended if the humidification has been done at low RH. If the conditioning has been done at high RH, the time of second exposure to $SiCl_4$-ozone will determine the hardness to some extent. No increase in hardness of surface, however, will result from exposures over 2 hr in length. Concentrations of $SiCl_4$ and ozone are the same as in the first exposure period.

During this second exposure, bright interference colors become apparent on the surface of the plastic. Variations in the thickness of the hardening film are indicated by the spotty or uneven character of the interference patterns. It has been found that the ozone must be present to insure an even deposit of the hard material on the plastic surface. A fully developed interference bloom on the surface indicates that the exposure to the vapor mixture is complete.

A final conditioning in the humidifier at the RH used for the second conditioning for an hour concludes the treatment. It has been found desirable to allow the larger samples to stand for a few days after treatment, so that the film may set.

While the above description of treatment is for Lucite, a similar procedure has been tried on CHM and on styrene. In the case of CHM, however, the film tends to be a little cloudy. Initial conditioning at low RH (50 to 60 per cent) for the longer time intervals is recommended to minimize this effect. Original faults and blemishes on the surfaces of CHM samples are intensified more by the hardening treatment than in the case of Lucite.

The treatment for Lucite, when applied to styrene, increases its hardness by a factor of 5 to 15. A modification of the technique in a single experiment on styrene, however, has been found to increase this factor to 20 to 30. In this experiment, the preliminary conditioning was at 75 per cent RH for 77 hr, exposures to $SiCl_4$ and ozone were for 1 hr each time, and intermediate conditionings were at 75 per cent RH for 20 hr each. The samples gained in surface hardness by a factor of nearly 30.

Tabulation of Results. The increased hardness of surface produced by application of the $SiCl_4$-ozone process to various plastics is exhibited in the last column of Table 8. Hardnesses are also given for the newer plastic material, EDM, developed by Polaroid.

It is evident from these preliminary experiments that further investigation to establish details for the processing of CHM and styrene is desirable. For an industrial process, a flow treatment would certainly be advantageous. The outstanding merits of the $SiCl_4$-ozone process are that the treatment is done by gases and is carried out at temperatures below the softening point of the plastic. Objects of any shape can be treated without danger of deformation.

Silicon Tetrachloride—Nitrogen Dioxide Treatment. A second method of obtaining hard films has been tried sufficiently extensively to warrant further consideration. The procedure is similar to the $SiCl_4$-ozone procedure, but the latter is replaced by nitrogen dioxide (NO). Alternate exposures to air of controlled RH and to a mixture of $SiCl_4$ and NO are made. The concentration of $SiCl_4$ is again 0.8 ml per liter and NO is used at partial pressures of 10 to 100 mm of mercury. Two exposures to the vapor mixture have been found sufficient to harden Lucite to values between AN 11 and AN 20. The hardened surface is not as uniform, however, as in the ozone process. Orange-peel irregularities are evident in reflected light, application of the process in its early stages to CHM was not successful, and the surface invariably became cloudy and rough. By careful control of the humidity, however, this method might be developed usefully for CHM and other plastics.

8.7 OPTICAL QUALITY OF PLASTIC LENSES, PRISMS, AND FLATS

The quantitative measurement of surface irregularities and of internal variations in refractive index of CHM and styrene optical elements has been carried out at the Massachusetts Institute of Technology.[8] An attempt to evaluate the optical quality of plastic elements

[redacted]

as compared to glass and to give illustrations of their optical behavior forms the subject of this section.

In general, the optical tests have consisted of:

1. A study of the image formation by plastic lenses.
2. A comparison of the surfaces of plastic lenses with test glasses of known curvature.
3. A study by interference methods of the surfaces and internal structure of plastic prisms and flats.

8.7.1 Image Formation by Lenses

Three of the T-108 telescope objectives (see Figure 11 for photograph) have been compared with a production T-116 glass objective

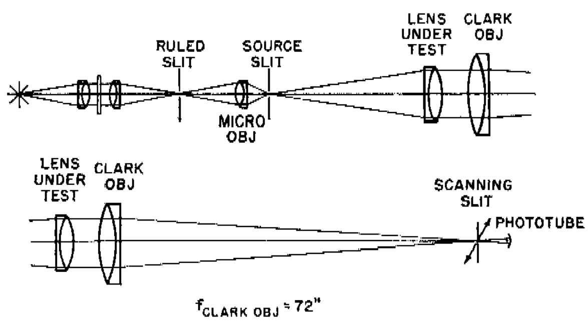


FIGURE 20. Optical system for scanning lens images.

lens element furnished by the Frankford Arsenal. The T-116 telescope is similar to the T-108 but has glass optical elements throughout. For comparison, measures have also been made on a high-quality achromatic objective having a focal length of 30 in.

The T-108 objective has a focal length of 15.08 in. and the elements are made of CHM and styrene. All the plastic elements showed some astigmatism and one of them had "pull-away" faults and irregular local refraction. The measures were made in such a way as to minimize the influence of astigmatism. A mercury vapor source was used to eliminate chromatic aberration as far as possible.

Three methods of examining the images formed by these lenses were used.

Method I. In the first method the lens to be studied was used to collimate the image of a slit. The parallel rays from this lens were then refocused by an excellent Clark astronomical objective, 6 ft in focal length, to form an image which could be scanned by a second movable slit, behind which was placed a photocell and amplifier system. Figure 20 shows the optical arrangement used for these tests.

Since the ruling of a uniform slit narrower than 0.005 mm and of adequate length was a

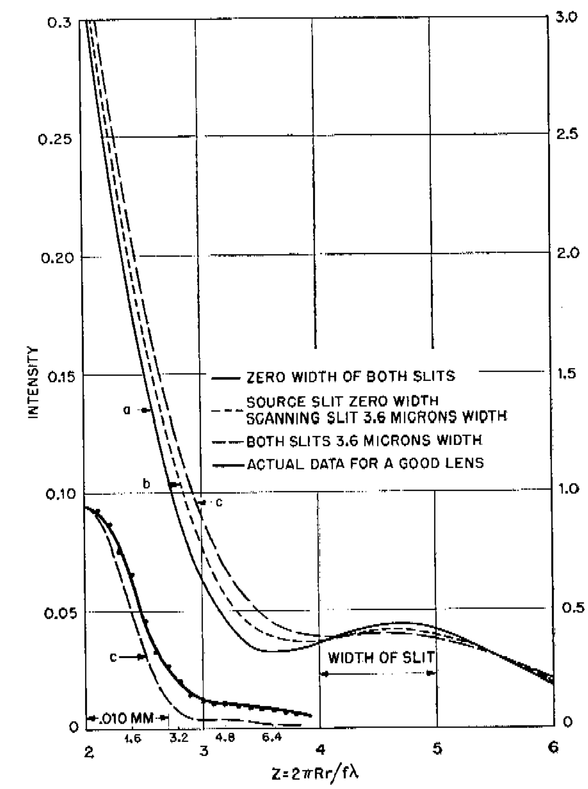


FIGURE 21. Diffraction patterns due to finite slit width.

difficult task, the slit actually used for the source was the optical image of the physical slit produced by a microscope objective of 48 mm focal length, so that the effective source was about 0.003 mm wide. The slit illumination was provided by a mercury lamp (AH-4 GE).

The image of the source produced by the Clark objective was nearly 0.04 mm between secondary diffraction maxima. With a scanning slit 0.005 mm wide, adequately fine coverage of sections of the image was obtained. The scanning slit was attached to a micrometer screw so that lateral displacements could be meas-

ured to 0.001 mm. Readings at different positions across the image could be taken as desired. An RCA 931 photomultiplier tube with associated amplifier was used, the output of which could be read on a microammeter. The circuit diagram of this recorder is published in an MIT report.[8a]

It was found by experiment that the scanning slit could be placed satisfactorily in the focal plane of the Clark objective by visual inspection. This was checked in several instances by scanning the image at a few points in the neighborhood of the focal plane and picking from the response curves the position giving maximum image intensity.

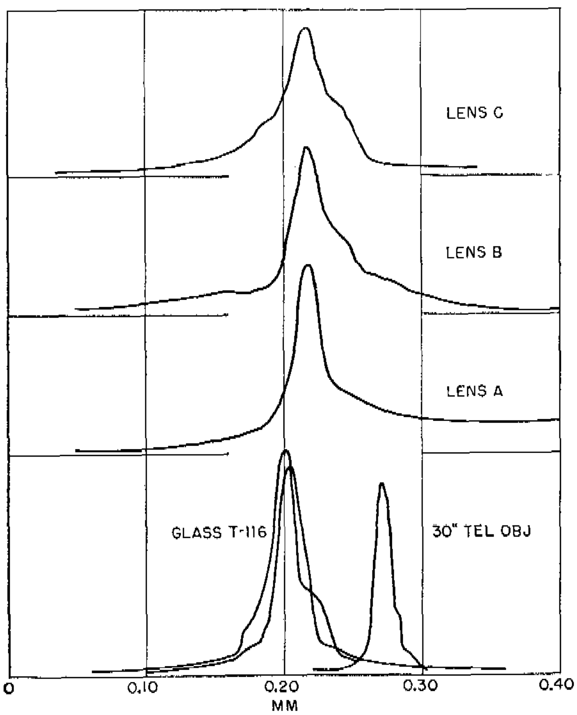


FIGURE 22. Image profiles for plastic and for glass lenses.

In order to judge the merits of the respective lenses whose image patterns were scanned with this apparatus, one must bear in mind the results to be expected from a more or less ideal test. Effects of finite source slit and finite scanning slit must be considered. To this end, data were taken on the best astronomical objectives at hand and compared with the theoretical curves computed on the basis of diffraction theory. The results are exhibited by the curve of Figure 21. The necessary data for computing the theoretical curves have been given by Selwyn.[9]

Curve *a* shows the pattern to be expected from an infinitely narrow slit, *b* shows the pattern to be expected from the scanning of *a* by a slit of finite width, and *c* shows the pattern to be expected in scanning the image of a finite slit with another finite slit. The slit widths used in calculating curves *b* and *c* were those currently in use in the optical system shown in Figure 20. The abscissa scale is in units of the scale used by Selwyn, $Z = 2\pi Rr/f\lambda$, in which r is the distance from the pattern center, R the lens radius, and f its focal length. The equivalent value of scanning slit width is also indicated. In addition to these three curves, one complete half-curve of type *c* is shown on a scale to make it comparable with the curve formed from scanning data on the perfect lens assumed in the computations. The degree of approach of the measured characteristic to the theoretical is evident from the figure.

The profiles of the slit images obtained by scanning the plastic lenses, and also those from the T-116 glass objective, are shown in Figure 22. The two curves for the glass lens were taken with the lens rotated about its axis at positions 90 degrees apart. The profile for the 30-in. glass objective indicates an asymmetry which is probably due to the source slit. It is apparent from the figure that none of the plastic lenses match the comparable glass objective T-116 in concentration of light. This, of course, is a measure of resolving power.

A second indication of the relative resolving power of the lenses is furnished by the tracings shown in Figure 23. The single source slit has been replaced here by a group of five parallel slits. The spacing between centers is 0.015, 0.025, 0.038, and 0.050 mm. The widths of the slits are indicated at the bottom of the figure. Clearly, the scanning method separates the slit images which are 0.025 mm apart. This would indicate a resolving power of 40 lines per mm, but one must bear in mind the limitations imposed by the scanning method. By comparing the theoretical curves of Figure 21 with the corresponding data curve for the perfect lens,

one sees immediately that the scanning method underrates the visual resolving power of the lens. A further visual test confirms this. When a low-power microscope is used to examine the images of the usual black and white Bureau of Standards test chart[10] formed by the three plastic lenses, all show a resolving power of 100 lines per mm.

It is a common observation of those using small telescopes with plastic optical systems that scattered or diffused light is a particularly objectionable feature. This has been brought out elsewhere[11] in some detail. The cause may lie in abnormal lens zones which divert perceptible amounts of light from the proper image location. The definition of the lens may not be seriously impaired, but the contrast is significantly reduced when dark objects are viewed against a bright background.

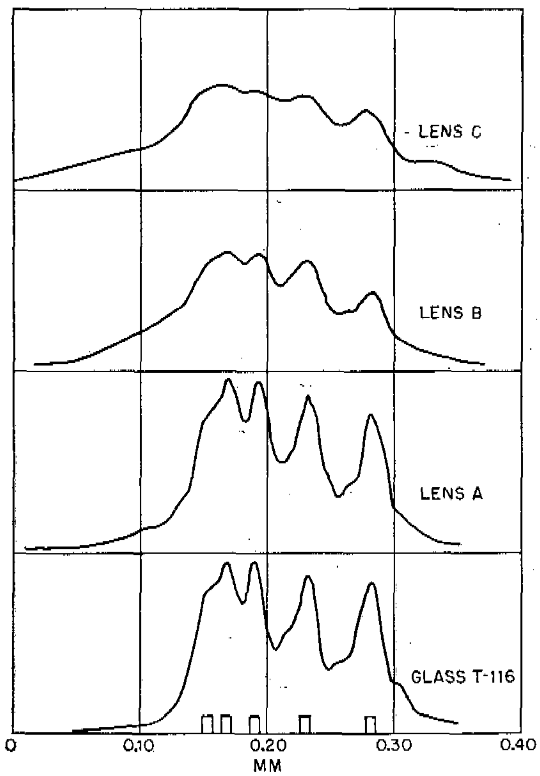


FIGURE 23. Image profiles due to multiple slit.

An indication of the amount of light scattered into the image of a dark line when the surrounding field is bright is shown by Figure 24. Dark lines, made by ruling and then photographing on high-resolution plates, were imaged by the four lenses (three plastic, one glass) under test and scanned in the usual manner. Widths of these source lines varied from 0.005 to 0.020 mm. Profiles of the images constitute Figure 24. Before the profiles were taken, the lens under test was mounted in the position which gave the best visual perception of the finer lines. The amount of light scattered into the image of a line by the background is indicated by the extent to which the intensity falls below that of the background for the finer lines as compared to the broader lines. One cannot draw quantitative conclusions regarding visual performance from these curves because the method is not directly comparable. The method does, however, provide a valuable objective comparison between different lenses as regards scattered light.

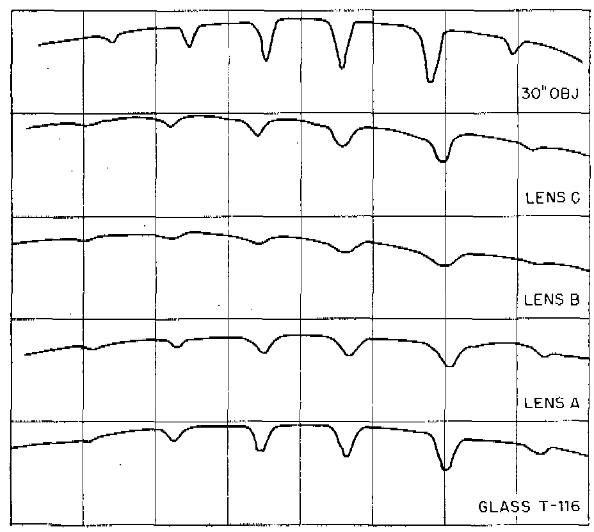


FIGURE 24. Image profiles of opaque rulings.

Method II. The second method of obtaining a record of the comparative image-forming characteristics of plastic and glass lenses consisted in photographing the monochromatic image of a pinhole source. The lens under test was used to collimate light from a round pinhole about 0.015 mm in diameter. Mercury green radiation was used for illumination. The image of the source, formed by the Clark objective, was magnified by a 32-mm microscope objective and photographed on 35-mm film. Pan-X emulsion was used to photograph the images formed by the T-108 and T-116 objec-

[redacted]

tives. For the 30-in. glass objective, Microfile film was used in order to record the detail of the high quality image.

Figure 25 displays the character of the image as a function of parfocal position for the lenses. In the case of the T-108 objective, the pictures correspond to intervals of 0.043 mm in image space. The corresponding figure for the T-116 is 0.048 mm. Overall magnification between image and print is about 32× for all except the 30-in. objective for which it is about 50 diameters. It is well to note the relatively more diffuse and complex character of the images formed by the plastic lenses as compared to those of the T-116 glass objective. The 30-in. objective image is shown only as a more or less ideal type. It should not be compared directly with the others.

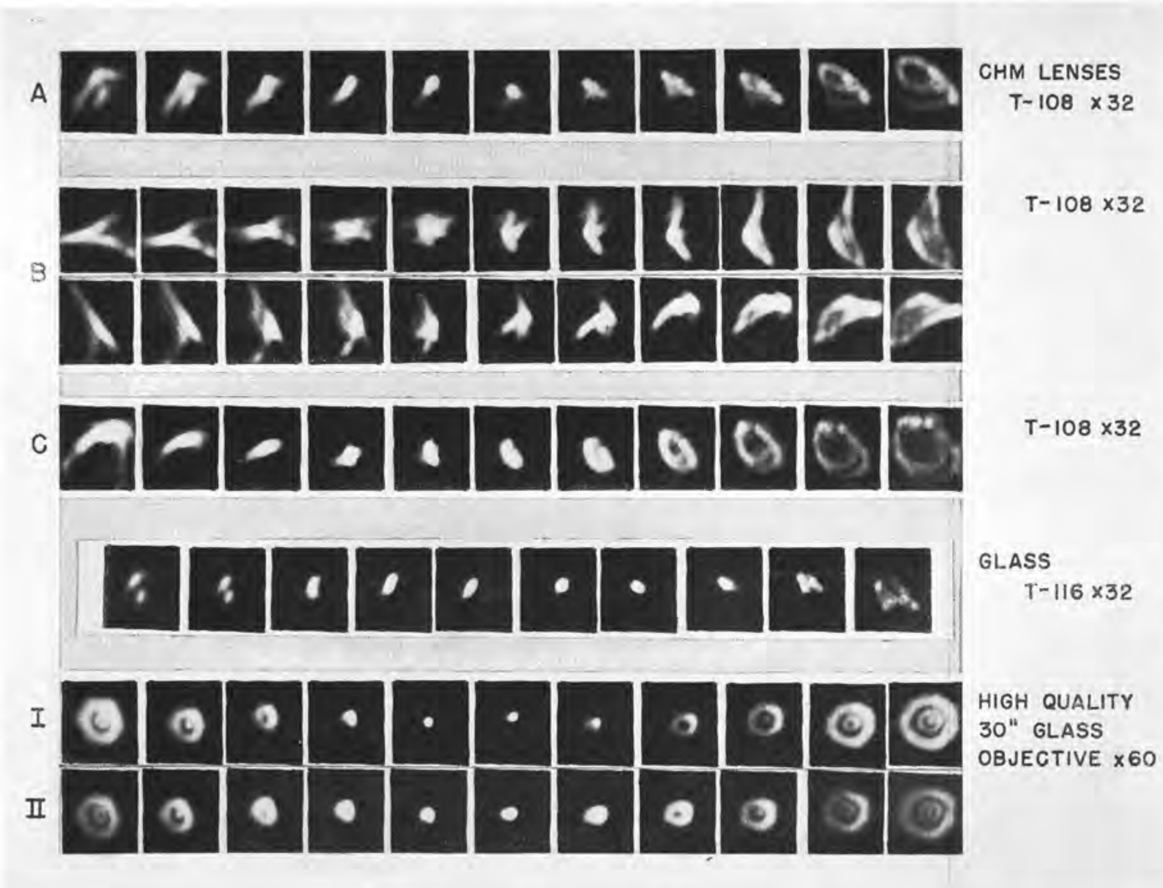


FIGURE 25. Parfocal images of a pinhole source.

Method III. A third method of examining the distribution of light in an image has been described in detail by L. A. Jones and R. N. Wolfe.[12] Their method consists in photographing the image of a line source, such as an incandescent filament, through a wedge of gelatin in which colloidal carbon has been suspended. If the wedge has a constant angle, its density gradient will be nearly constant. In the present instance a gradient of 1.34 per cm was used.

When the image of a uniformly bright line source is photographed through the wedge, its gradient being parallel to the line, the limits of the developed image represent a logarithmic plot of intensity distribution in the image.

Images similar to those scanned photoelectrically were magnified 24.5× by a microscope objective and photographed with the gelatin wedge directly in front of the photographic

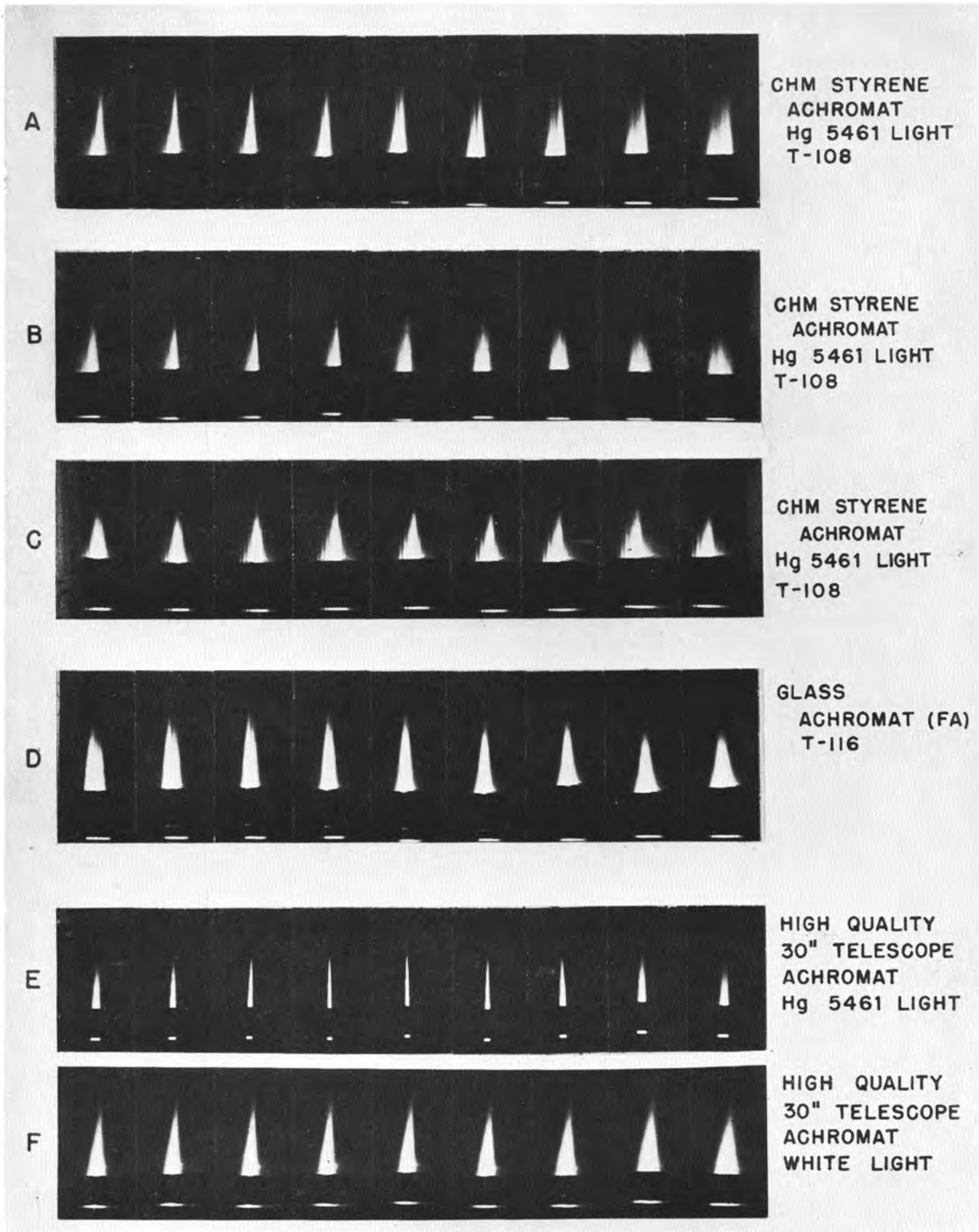


FIGURE 26. Intensity patterns of image of line source produced by plastic and glass lenses.

plate. A series of exposures was made at different positions near focus by moving the microscope and camera in steps of 1.0 or 0.5 mm. The resulting wedge pictures are shown in Figure 26. Mercury green light was used in all cases except one; that was for a glass lens, in which a 1-w pyrometer filament lamp was substituted for the original slit. When inter-

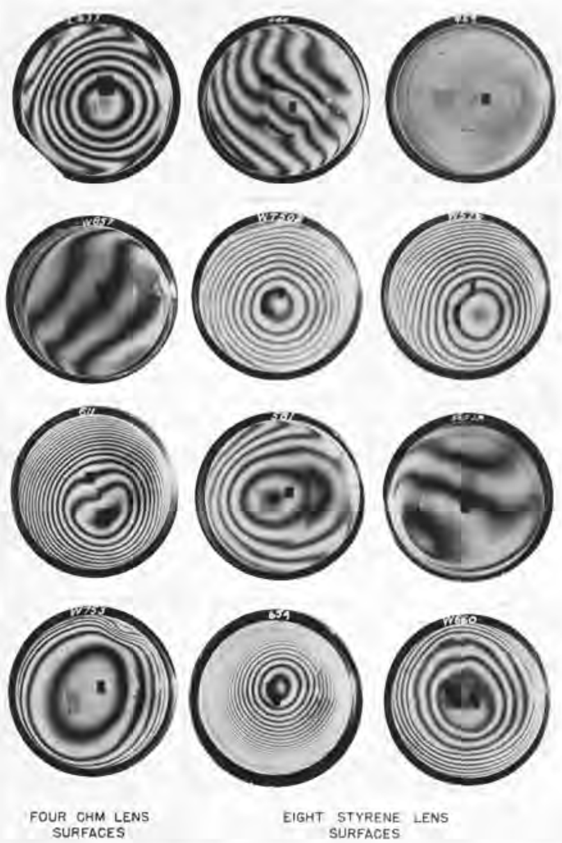


FIGURE 27. Interference patterns showing local accuracy of CHM and styrene lens surfaces.

preting these pictures qualitatively, it should be borne in mind that a perfectly sharply defined image of any width would record as a shaded rectangle. The presence of a greater concentration of light in the center than at the edge of an image results in the peaked pattern. The more diffuse and spread out the image, the less sharp will be the wedge picture. These photographs confirm the results of the pinhole tests in showing superior imagery on the part of the T-116 glass lens as compared to the plastic T-108. No quantitative measures of light intensity were made in this examination of plastic lenses.

8.7.2 Surface Curvatures of Plastic Lenses

In the study of plastic lens performance, the figure of the surfaces of twelve styrene and four CHM lenses, cast in molds for the positive components of the T-108 objective, has been investigated. The first aim was to study the local irregularities of the cast plastic surfaces. Therefore, two test surfaces of Pyrex glass were used, one figured to match each face of the finished lens component. Since the radius of the test glass designed to test the shorter radius of the lens was longer than any of the radii found in the samples, the measurements were made at a somewhat elevated temperature (about 38 C). Otherwise, an excessive number of interference fringes would have been observed between test surface and sample.

Photographs of the interference patterns formed between the test glass and the shorter radius surface of the plastic lens were made in sodium light. Some of these are shown in Figure 27. In all cases the plastic was allowed to reach temperature equilibrium with its surroundings. Since the room temperature was not the same for all the pictures of Figure 27, no attempt should be made to compare the surfaces quantitatively with the test glass by counting these interference fringes.

Five of the most regular surfaces, as shown by the interference patterns, and one other were selected to determine quantitatively the departure of the surfaces from spherical form. This was done in the usual way by measuring the diameters of the interference rings of successive orders and comparing the run of diameters with that to be expected if the surfaces were perfectly spherical. In obtaining a formula for the relation between a given ring diameter and the phase retardation in wavelengths between reflected rays at the two surfaces of the interface, three corrections must be considered. First, the interfering rays are not normal to the lens surface in the interference interspace; second, the normal is not

parallel to the sagittal intercept on the lens axis; and, third, the curvatures are so great that the sagitta exceeds that given by the simple formula, $h^2/2R$, where h is the radius of the zone of the interspace considered, and R is the radius of curvature of the surface.

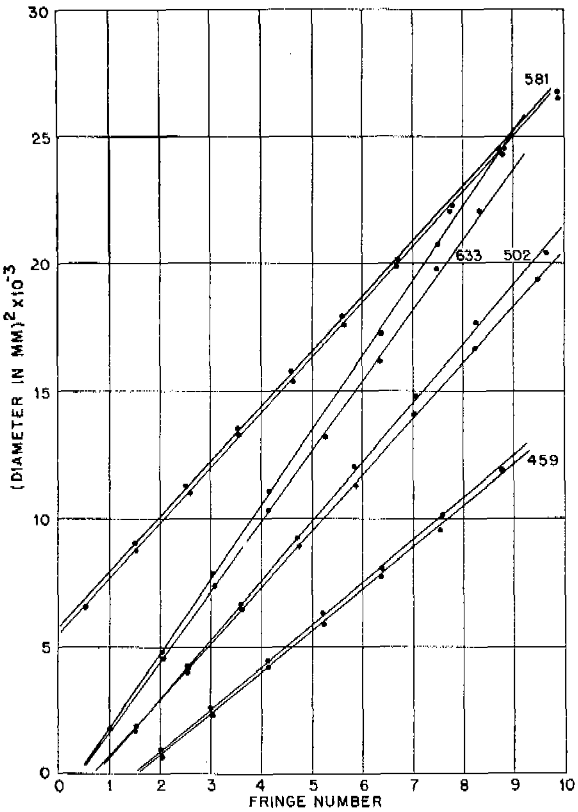


FIGURE 28. Departures of surfaces of plastic lenses from sphericity.

These corrections are readily expressed in mathematical form, with the result that we obtain the basic interference equation for the mth ring:

$$(m + e)\frac{\lambda}{2}\left\{1 + \frac{d^2}{4}\left[\frac{1}{4R^2} + \frac{1}{2}\left(\frac{1}{f} + \frac{1}{R} - \frac{1}{p}\right)^2\right]\right\} = \frac{d^2}{8}\frac{R_t - R}{R^2}$$

where f, R, p, e are the focal length, radius of curvature of interference face, distance from the face to the camera lens, and a fraction, respectively; R_t is the radius of curvature of the test glass; and d is the diameter of the mth interference ring. If the surface were a sphere of so long a radius that the corrections in the brackets could be neglected, the integral orders of rings plotted against d^2 would fall on a straight line, whose intercept at $d^2 = 0$ indicates the value of e. If the surfaces are steep and the rays oblique so that the correction is necessary, it may be computed for each d^2 and the left-hand side of the equation will then be proportional to d^2.

Measurements of four surfaces, corrected and plotted, are shown in Figure 28. Each surface pattern was measured on two diameters normal to each other. The departures of these surfaces from sphericity, evident from the figure, are not serious.

Probably the least important deviation of a lens from a standard dimension is in the radius of curvature (or in the curvature defined as the reciprocal of the radius of curvature). However, one of the purposes in testing the surface was to note how the radii of the lens specimens tested varied in their relationship to the radius of the test glass. The measures were made in a room at a controlled temperature sufficiently high (about 38 C) to insure a reasonable fit between the two surfaces for all the specimens.

The method of measurement was simple. The number of fringes of sodium light within a circle of 2-cm radius was counted for each surface. This number is directly proportional to the sagittal difference between the spherical surfaces; each fringe observed indicates a difference of 1.5×10^{-6} mm^{-1} in the curvatures of test glass and lens surface. The results of these measures are shown in Table 9. Column 1 gives the number of the lens surface, columns 2 and 3 give the deviation in fringes between test glass and each lens surface. If these numbers are added algebraically, multiplied by n-1 (0.50 for CHM and 0.59 for styrene), and multiplied by 1.5×10^{-6} we obtain the deviation in power, or reciprocal focal length, due to the surface departures. Column 4 shows this deviation. Since the corresponding focal power is $5{,}900 \times 10^{-6}$ for the CHM lens and $6{,}960 \times 10^{-6}$ for the styrene lens, the overall deviation of these lenses does not exceed 0.5 per cent. A positive entry in Table 9 means that the surface under test has a greater curvature than the standard. There is no evidence that departures of curva-

ture in one surface tend to be compensated by departures in the other surface. The molds from which these lenses have been cast are designated in column 5 of Table 9.

TABLE 9. Deviations of lens surface curvatures from a standard test glass.

Lens		Curvature difference* fringes (R_1)	(R_2)	Difference $\frac{1}{f}$	Molds (R_1)	(R_2)
CHM	611†	−3	10	5×10^{-6}	7X	225L
	633	−1.5	−6	−6	"	"
	753‡	−5	5	0	"	"
	857§	−3.5	3	0	"	"
Styrene	446	−5.5	−2.5	-7×10^{-6}	7X	225L
	447†	−5.5	3	−2	338A	L55
	458	−6	1	−4.5	7X	"
	459	−5.5	−5.5	−9.5	"	"
	471	−4	1	−2.5	338A	225L
	472	−7	2	−4.5	7X	L55
	502	−10	6	−3.5	"	225L
	576‖	−5.5	7	1	"	"
	581¶	−2	−7	−8	"	"
	589	−8.5	1	−6.5	"	"
	654	−11	−12	−20	"	"
	660†	−5.5	9	3	"	"

* Nominal radii: $R_1 = 265.0$ mm, $R_2 = 124.7$ mm
† Both surfaces very irregular
‡ Edge fault in R_1
§ R_1 queer
‖ R_1 irregular
¶ R_2 irregular

8.7.3 Interference Tests of Flats

The optical behavior of the plastic materials, CHM and styrene, was examined further by obtaining interference patterns on the surfaces of nearly flat, thick slabs, 4 in. in diameter, and comparing these with transmission patterns observed with a Twyman-Green interferometer. In general, the plates were not perfectly flat, but had one concave and one convex surface of some 100 to 200 m mean radius.

The surfaces of the plates were examined against a good glass optical flat. Photographs of several of these fringe patterns are shown in Figure 29, A and B. Some of these cover only the central three-fourths of the plate, since the mercury illuminating system had a restricted aperture. Others, made with sodium light, cover the full aperture.

To investigate the departures of the surfaces from spherical form, the fringe patterns were measured along major and minor diameters. For successive fringes, tabulation was then made of the diameters squared. The first differences of these squared diameters should be constant for a spherical surface if the angle subtended at the camera lens is not large. Obliquity corrections for larger subtended angles would not exceed ⅛ fringe and could safely be omitted even for the most highly curved surface.

The departure of the diametral surface sections from circular form was found to be very small. In Figure 30, the values of d^2 for successive fringes, as shown by CHM sample 377, are plotted. The departure of the abscissa of a plotted point from the straight plotted line, in fringes, indicates the departure of the corresponding zone from the sphere in half wavelengths of the sodium light used. The lines drawn represent the best sphere with a diameter of 2.5 in.

Figure 29 also shows the transmission interference patterns photographed with the Twyman-Green interferometer. A comparison of the surface fringe pattern with the transmission pattern enables one to draw conclusions regarding the internal homogeneity of the plates. Each fringe of the surface pattern means an increment of surface departure of one-half wavelength. When a beam is transmitted once through an imperfect surface, there will result a local deviation of $n - 1$ half wavelengths (n being the refractive index of the material) for each fringe observed by interference with a test flat. When both surfaces are not plane, the algebraic sum of their respective fringe-pattern counts must be used.

In the interferometer the beam traverses the surface twice. Thus, for each surface fringe, there will be in the interferometer a retardation of $n - 1$ whole wavelengths, each of which is indicated by 1 transmission fringe. For CHM, of index 1.50, every 2 surface fringes correspond to 1 transmission fringe if the material is optically homogeneous. For styrene of index 1.59, 1.7 surface fringes correspond to 1 transmission fringe.

The less complex patterns shown by the styrene specimens I and II, Figure 29B, allow a more satisfactory comparison of the surface

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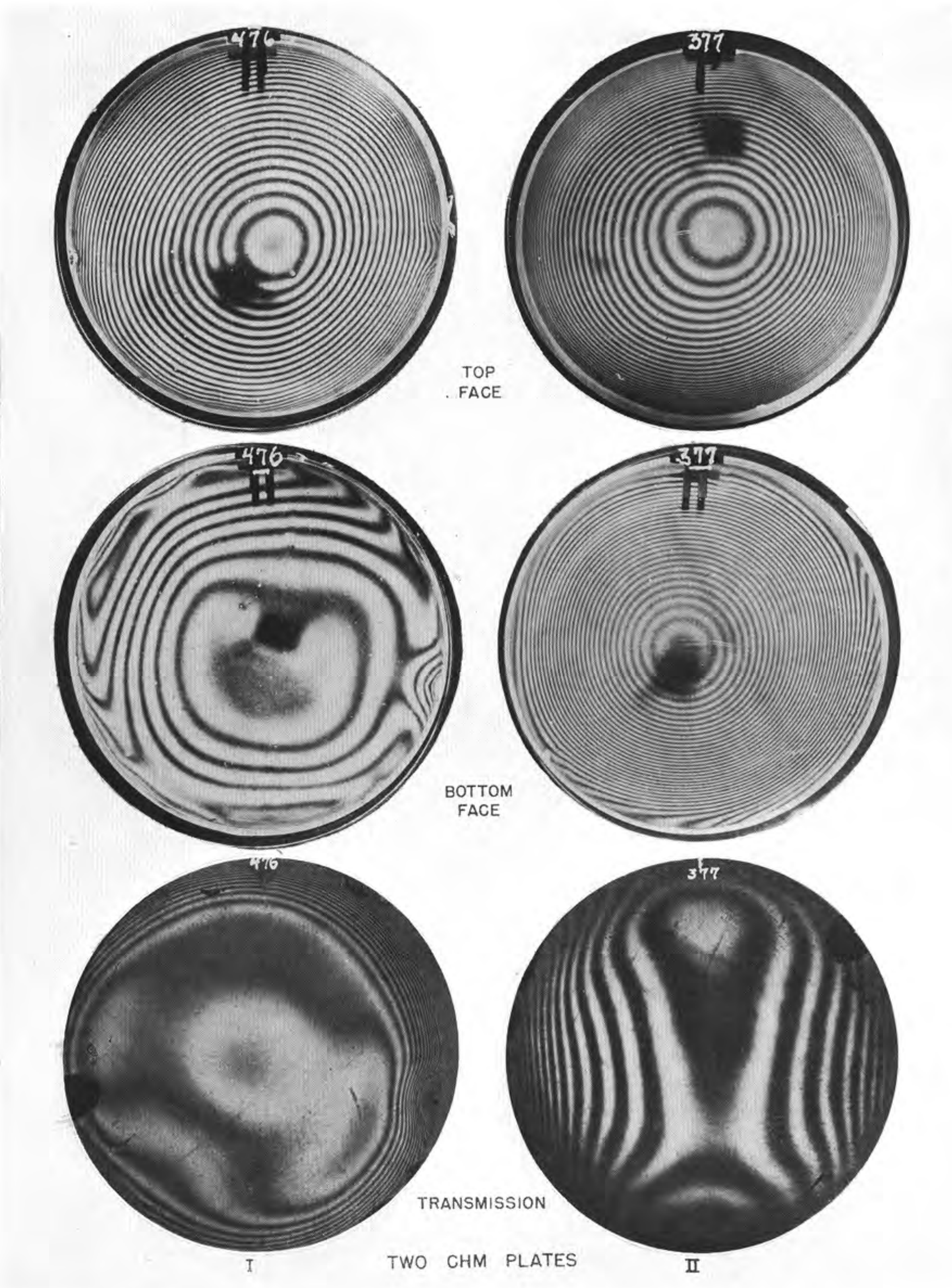

FIGURE 29A. Interference fringe patterns for flat disks of CHM and styrene.

[redacted]

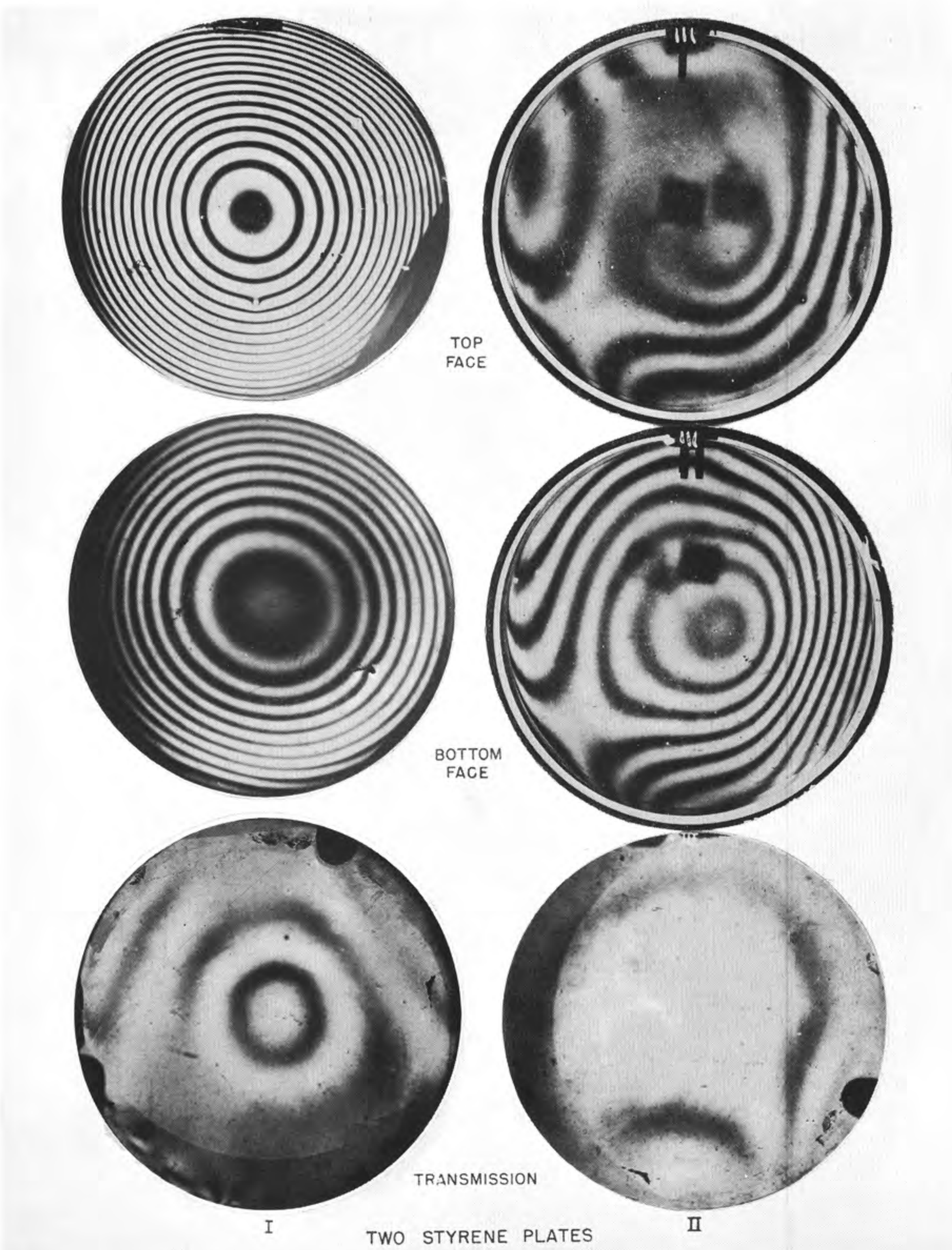

FIGURE 29B. Interference fringe patterns for flat disks of CHM and styrene.

[redacted]

and transmission characteristics than do the more irregular CHM patterns. Sample II has one surface that is so nearly flat except near one edge that the transmission pattern can be ascribed to the other surface alone. The similarity of the transmission pattern to that for the curved face, allowance being made for the 1.7 ratio, shows that the internal optical structure of the sample is remarkably uniform.

In the case of sample I, a different procedure was used. From measures of diameter, the

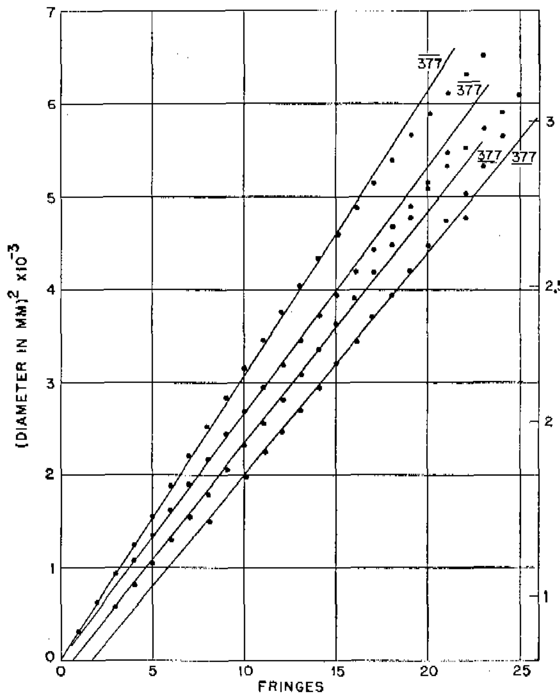

FIGURE 30. Departure of surfaces of CHM plate from spherical form.

fringes were located relative to an estimated center and plotted as shown in Figure 31. Ordinates are the successive numbers of half wavelengths. A curve was drawn for each surface pattern at corresponding diameters. At an abscissa point where these surface curves are 1.7 fringes apart in ordinate, the first transmission fringe should be found. Where the surface curves are 3.4 fringes apart, the second transmission fringe should be found, and so forth. When analysis of styrene sample I is made in this way, the fringes of the transmission pattern are found where they are predicted, within the accuracy of measurement.

The conclusion to be drawn from these patterns is that, for styrene, optical inhomogeneity is insignificant compared to the accuracy of figure of the molded surface. The patterns indi-

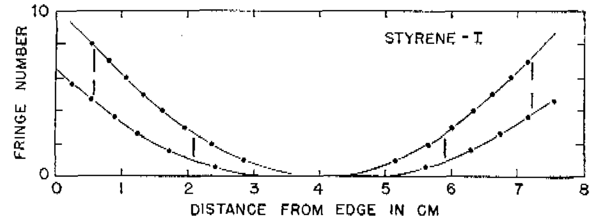

FIGURE 31. Surface deviations of styrene plate for comparison with transmission fringe pattern.

cate a constant refractive index in the styrene samples tested to within 4 parts in a million (or 0.000002 in the index itself).

Corresponding analyses for the CHM sam-

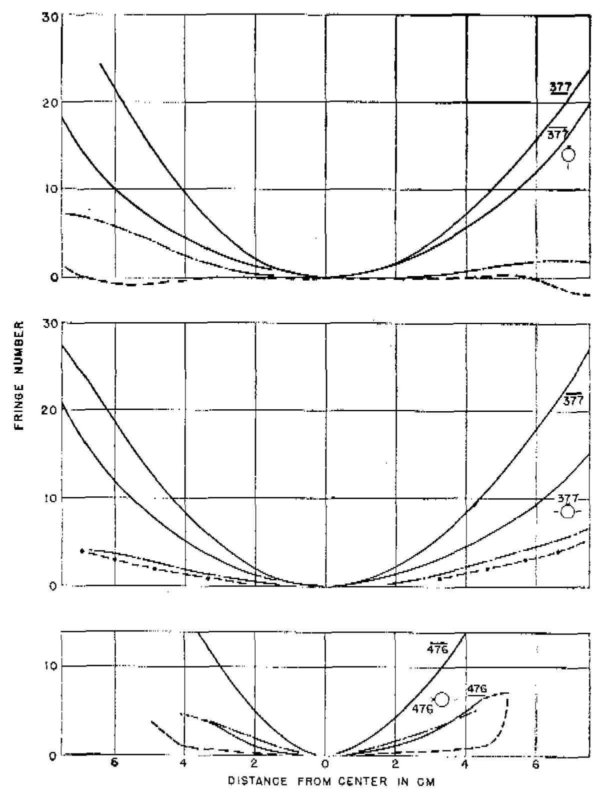

FIGURE 32. Surface deviations of CHM plates correlated with their transmission.

ples are shown in Figure 32. They are not nearly as conclusive in this case because of the greater irregularity of pattern. There seems to be a tendency for excess optical density in the

outer zones of the plates tested. In Figure 32, the heavy long dashed lines are the transmission pattern cross sections predicted from the surface curves; the thick broken lines represent measures made on the transmission patterns. The discrepancy between predicted and observed patterns is several times greater with these CHM samples than with the styrene sample tested.

It must be borne in mind, in evaluating these results, that the surface patterns are very susceptible to temperature fluctuations while the transmission patterns are not. All possible precautions were taken to minimize these effects.

8.7.4 Interference Tests of Prisms

Four 90-degree total reflecting prisms and six 60-degree prisms, all of styrene, were examined for surface and internal optical quality. The surfaces of the 90-degree prisms were photographed in mercury green illumination against an optical flat, with the results shown in Figure 33. It is evident that the faces are far from plane. No attempt was made to evaluate the departures quantitatively, because of their size.

The observation of the transmission patterns in the interferometer required the use of a small pinhole source to resolve the fine-grained pattern. The 60-degree prisms were observed at minimum deviation, and the 90-degree prisms with the beam incident normally on the right-angle faces and with total reflection on the hypotenuse face. One of the elements (W-211) was also used as a 45-degree refracting prism. Figure 34 shows the interference patterns so obtained.

All of the prisms showed evidence of pronounced internal strain, which appears as local zones of ill-defined interference. Attempts to record the patterns in polarized light, with polarizer and analyzer crossed, were unsuccessful because of the faint illumination resulting from the small pinhole. One prism (V-903), however, was examined satisfactorily with the polarizer and analyzer parallel. The photograph obtained is shown also in Figure 34.

The irregularities shown by these patterns indicated the desirability of a direct check on the visual optical performance of the prisms. To this end, a Bureau of Standards chart[10] was set up at a distance of 70 ft, so that with a glass prism placed before a 12× telescope of 30-cm focal length the finest line pattern was not resolved but the next was easily resolved by two different observers. Then the best resolution with each of the 45-degree styrene prisms was obtained by setting it in turn in place of the glass prism. Refocusing was done each time to insure the best performance of each prism. The resolving power in lines per mm in the focal plane of the telescope is given in Table 10. All of the plastic prisms show considerably less resolving power than the glass prism used as standard and most of them have appreciable astigmatism.

TABLE 10. Resolving power of styrene prisms, lines per mm at focal plane of 30-cm telescope.

Observer	Glass		V 904		V 905		W 212		W 211	
	vert.	hor.	vert.	hor.	vert.	hor.	vert.	hor.	vert.	hor.
P	85	85	67	54	70	70	75	48	75	65
R	95	95	80	60	80	80	62	40	85	80

8.7.5 Conclusions

The evidence supplied by these examinations of an admittedly small number of plastic samples seems to rank the material decidedly secondary to glass, at least as the elements are fabricated at present. Most of the irregularities, however, in the symmetrical elements such as lenses and flats, appear to be surface defects which may be overcome with added improvements in the fabrication technique. It is to be expected that the prism faces show the least satisfactory optical quality because of the greater asymmetry in the contracting stresses.

Evidence from the interference patterns of CHM and styrene plates indicates that the latter is superior in optical homogeneity. The best styrene specimens show an index variation of about 2×10^{-6} over a 3-in. diameter specimen; the CHM variation is about three or four times as much. The index fluctuation is zonal in character and astigmatic in the one plate

[redacted]

thus studied. For both materials, there is no evidence of flocculent or other moderately fine-grained variation of index.

The presence of considerable scattered light in plastic optical elements, high thermal expansion properties, and surface irregularities are the features which for the time being limit the applicability of this material to other than low-power systems. A secondary disadvantage is their softness, which may be overcome by hard-

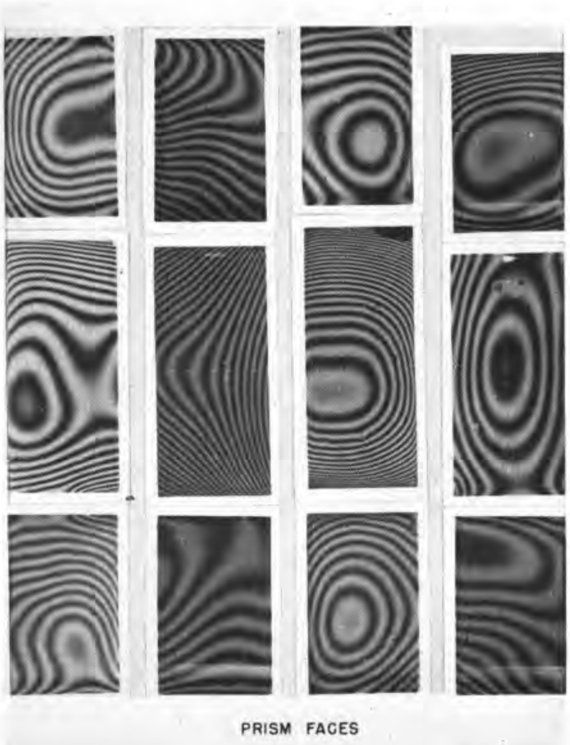

FIGURE 33. Surface deviations of four styrene prisms.

ening techniques or by the future development of hard cross-linked polymers.

8.8 RECOMMENDATIONS BY NDRC

The internal homogeneity of present plastic elements is excellent, but further work is indicated to improve strain, surface accuracy, haze, and surface hardness.

The development of cross-linked polymers appears to offer the most promising means for increasing surface hardness, but efforts should be continued to develop an improved method for depositing hard surface coatings by evaporation.

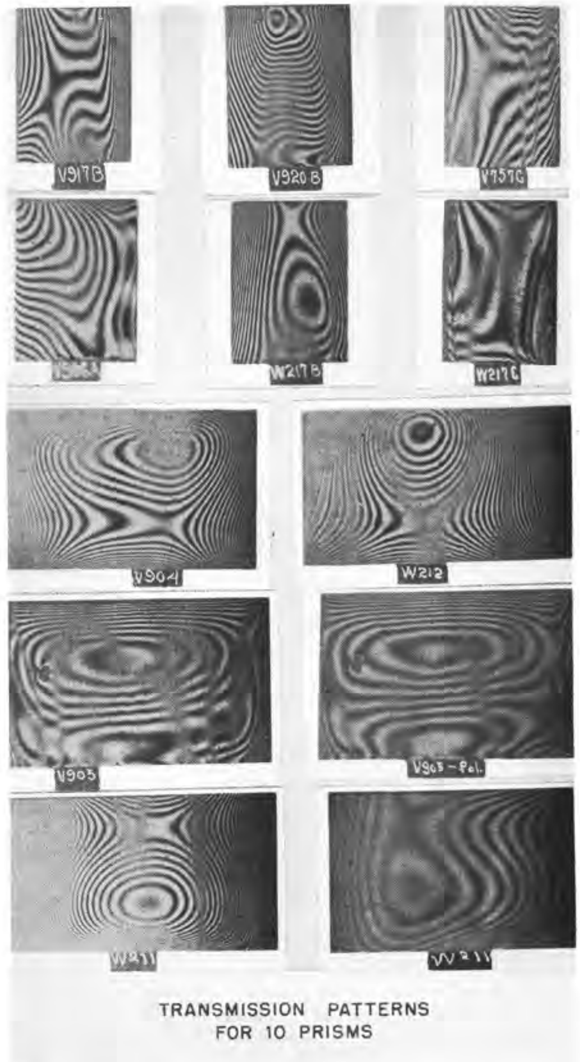

FIGURE 34. Transmission interference patterns of styrene prisms. The pattern V903-Pol. was taken in polarized light.

An extensive chemical program is indicated to explore many different types of compounds which have not yet been investigated. This program should aim to discover compounds which have favorable characteristics from the point of view of optical design. It would also be very desirable to develop plastics which have smaller temperature coefficients of index of refraction than CHM and styrene.

Chapter 9

OPTICAL TECHNIQUES

By *James G. Baker* and *H. F. Weaver*[a]

THIS CHAPTER describes several miscellaneous optical techniques. These include techniques for the grinding and polishing precision lenses and mirrors (Harvard University, Contract OEMsr-474), for grinding and polishing roof prisms (Mount Wilson Observatory, Contract OEMsr-101), the molding of glass lenses (Eastman Kodak Company, Contract OEMsr-421), the making of reticles (Edward Stern Company, OEMsr-293, and California Institute of Technology, Contract OEMsr-389), and the deposition of low-reflection and high-efficiency films (California Institute of Technology, Contract NDCrc-118, Vard, Inc., Contract OEMsr-529, and the University of Rochester, Contract OEMsr-160).

Some of these techniques were developed in the course of establishing shop groups capable of turning out quickly prototypes of optical fire-control instruments and cameras for the Armed Forces. Others were set up specifically to develop new techniques as an aid in the mass production of critical items.

9.1 METHODS FOR GRINDING AND POLISHING LENSES AND MIRRORS

The Harvard contract (OEMsr-474), devoted primarily to design and construction of equipment for aerial photography, required at the outset that fairly large optical and machine shops be set up to handle the difficult instrumental problems encountered in the air. Although the ensuing shop work emphasized precision of manufacture to a very large extent, rather than short-cut methods, a number of interesting procedures were developed.

The optical industry on the whole is one long known for the close keeping of trade secrets. To a very large extent, these secrets are procedures that ought to occur to any worker but which in practice seem to come only after years of often misplaced effort.

Outstanding opticians are most often men of inherent ingenuity and intelligence who think of their handicraft as an art rather than as a trade. These individuals professionally are often reluctant to reveal even to their fellow workers the ideas and methods that have solved their own problems. Consequently, very few textbooks exist that can aid a serious minded beginner. The future skilled optician most often learns through his own experiences.

In 1940, the United States possessed very few men with the training required for uninstructed fabrication of optical parts of large size. The onset of World War II found these few workers almost submerged by the need to organize unfamiliar production line techniques, train new workers, and fabricate individual optical parts. The skill in fabrication necessitated years of experience and therefore could not be passed to others. Almost without exception such workers in the optical industry responded to their imposed responsibility, and, as a very small group, are directly to be credited for a very major contribution to their country's good.

The years of intensive wartime application to production of a wide variety of optical goods produced large numbers of new workers of distinction. It is no longer considered that a precision optical worker must inherit his aptitudes beyond the possession of great patience, intelligence, and alertness.

The Harvard contract in 1942 was not in a position to borrow or obtain opticians of requisite training from established industries. It was necessary to train new men for the task by dint of many hours of trial and repetition. Fortunately, a group of amateur craftsmen existed locally which had years of experience at figuring large mirror surfaces to the highest

[a] Dr. Baker of Harvard College Observatory has compiled the first section of this chapter relating to "Methods for Grinding and Polishing Lenses and Mirrors." The other sections of this chapter have been compiled by Dr. Weaver of the University of California.

optical standards. These men were drawn into the project and throughout World War II proved the value of their own training and hobby. Where others had found that amateur workers rarely appreciate the need for output, in this case the pressure of the war and the experimental character of the work eliminated such problems.

The following pages will attempt a summary of optical procedures employed in the Harvard contract. It is hoped that these otherwise unreported comments will aid in further work under government contracts, and that the description of self-evident techniques in the optical trade will be taken as a serious effort by an organization starting from the sketchiest beginnings. In spite of the lack of the usual decades of industrial "know how," it is evident from the favorable test results in Chapters 1 and 2 and from the many successful aerial photographs that high standards of quality were achieved.

9.1.1 Manufacture of Lens Elements of Large Size

In connection with the optical and engineering design of a long-focus aerial lens system, it is vital that wisely assigned tolerances be met in the optical and mechanical shops. To this end arise a number of details demanding incessant care by the workmen. The final experimental optical instrument is a kind of integration of a common effort. Rarely is it that an accident in manufacture can benefit a properly designed instrument. The perfected optical instrument is so unaccidental a product that it lies at the very pinnacle of many individual efforts and thoughts.

The following procedure for the fabrication of a large lens element became nearly standard in the Harvard Optical Shop.

1. Diamond milling to approximate curve and thickness of the required lens was done. The quality of the milling was limited by the type of diamond machinery available, but in practice was within several thousandths of an inch of the desired geometrical shape. Proper excess on thickness of a milled blank depended partly on hardness and partly on the chemical nature of the glass. In general, a hard glass like BSC-2 could be finished satisfactorily from the milling stage if 0.020 in. of excess central thickness were permitted. A soft glass or an unstable glass like DBC-1 required about 0.040 in. excess.

2. Diamond milling of Pyrex tools followed. Pyrex tools were used instead of iron in order to minimize the time element in preparing radii, and in order to afford the optician a ready means for altering his radius by differential amounts during the fine grinding without destroying the essential spherical surface.

3. Hand-grinding on a rotating spindle with an overhead arm and pin was the next step. Tool or lens was often pitched to a chuck for easy handling. Preferably, this chuck should have a standard thread for attachment to threaded spindles. In practice a 3.5-degree taper was adopted for all interchangeable spindle work.

4. Following diamond milling, grade No. 120 Carborundum was used for grinding. Thereafter, the steeper of the two sides was carried on to No. 320 and brought to good spherical contact within this grade. The radius at this stage was generally on the long side if concave, and approximately right if convex.

5. The lens was pitched to a special face plate attached to the centering machine. Tilting screws were adjusted until the lens as such was approximately centered relative to both faces at the same time that the No. 320 back face was running true, as measured by a dial gauge reading to 0.0001 in. In practice with the equipment at hand, the needle rarely fluctuated more than 0.0002 in. when properly adjusted.

6. The lens was edged to final diameter. Test for circularity and perpendicularity of edge to the reference smooth back was made by two dial gauges running on the respective surfaces. Usual demands required needle fluctuation to be less than 0.0002 in. at finish. This meant that the edge was sufficiently perpendicular to the back for all practical purposes.

It is necessary that the edging be parallel to the lens axis in order that a conical edge be avoided. The usual edging machine has a back and forth sweep movement. This movement

should be long, and the lens should be allowed to grind itself out at the chosen diameter. Tolerances on absolute diameter usually ran to within 0.001 in.

The optician has a constant struggle with thermal effects on his gauges and standards, as well as effects of coolant and grinding. It is important that the final stages of edging be done slowly if an accurate absolute diameter is to be achieved, and that all gauge measurements be referred to standards at the same temperature. In the Harvard shop the primary standards were Johannson gauge blocks.

7. The edged lens was now put through No. 320 Carborundum on the rougher side, and brought to radius also. During this process the centering of the lens was checked by a dial gauge. A stand was set up for the purpose with an adjustable set of three balls for support of the lens element in a horizontal position. The edge of the lens rested against two upright smooth metal posts. The five points now defined a fixed space reference for the lens element. Finally, a brass-tipped 0.0001 dial gauge pointer was adjusted against the surface with the point directly over one of the three reference balls.

The optician now made variation in thickness measurements at equally spaced intervals around the periphery. With spherical surfaces, the centering error was immediately determinable. The optician corrected the centering by uneven pressure as required on the side of the lens opposite the reference face. It was always important to center at each stage of fining to a fraction of the amount of glass to be removed during the next fining stage in order that spherical surfaces might be preserved.

8. Fining, centering, and radii adjusting were carried on by the skill and attention of the optician until the polishing stage. From stages where the use of emery for grinding is begun, radii were checked by a radius measuring microscope arrangement. To aid in this determination, 5-min. temporary polishes were given the concave surface to be measured, whether lens or tool. Change of radius was accomplished by stroke and pressure. Fining was most often carried on by automatic machine, followed in the last stage by careful handwork. The hand-centering procedures generally added only an hour or two to the total lens work.

9. Polishing was accomplished by hand and machine, as required. Polishing time depended on excellence of the fining, weight, speed of stroke, and on the polishing material. During the last half of World War II, Barnesite was used almost exclusively on all types of optical glass polishing. Figuring was accomplished mostly by hand on a slowly rotating spindle.

10. A finished 10-in. diameter lens element usually had the following characteristics: Each surface would be figured to better than one-quarter wave of green mercury light with emphasis on smoothness of figure, especially radially; each surface would have a radius within one part in two thousand or better; the lens would be circular and within 0.001 in. of an assigned diameter on an absolute basis; centering would show less than 0.0002 in. variation in thickness around the edge of the lens; central thickness would be within 0.005 in., since better accuracy rarely mattered in large optical systems.

Quality of polish obtained during the latter stages of World War II was uniformly excellent. Barnesite was the greatest single factor in this success. Earlier, it was found that glass types differed widely in their responses to figuring techniques which varied widely also among workers. From all around experience it would seem that the polishing agent was much more important to final polishing quality than was dust and emery contamination on laps. Indeed, it is very improbable that floating emery ever failed to get between the polishing surfaces. Quality of polish was most often tested by placing the lens in a strong beam of directed light, viewed against a black background. Better polish than shown by this test for aerial purposes was unnecessary. Such a test will show fine sleeks very easily.

Many times during the project, concave lens surfaces were mounted by means of a flat ledge around the edge of the lens. This flat ledge was hand-ground with emery on a flat iron plate, and was as carefully centered as were the surfaces. The machinist found flat ledge references necessary for accurate work. The optician

minded the extra work very little. The flat ledge usually served as a definitive seat for the lens with known sagitta.

Ever present in all figuring work are temperature effects. The optician is obliged to wait until a lens in contact with a test plate has reached thermal equilibrium before judging the results of his previous efforts. With large work, it proved necessary to enclose both pieces in a glass-covered box before reliable tests could be achieved. The skilled optician occasionally made thermal effects work in his favor by proper handling of lens and pitch lap. Almost all the skilled opticians found it possible to figure accurately, in spite of holding the lens element in the hands.

Thin lenses must be rested on edge before a reliable test of figure can be made. The disk is far more stable with edge support than with back support. For this reason all concave surface testing was carried out with the tool or lens on edge.

Beveling of lenses was accomplished most generally by means of fine emery and grinding in a concave diopter tool of adequate size. It was often deemed important to follow up the beveling by a slight bevel polish with felt and rouge or Barnesite. With soft glass types there seemed to be less tendency thereafter for fine edge particles to break off during the last stages of fine grinding and to cause time consuming scratches. It was of advantage to have a small hole in the bottom of the diopter beveling tool in order to prevent an air seal and difficulty of removing the element.

Thick lenses should not be edged in practice to a right circular cylinder, but instead should be slightly convexed. Ideally, the edge should have a spherical curve of diameter equal to the diameter of the lens, following the principle of a ball inside of a cylinder. In practice, the careful assembler rarely will tilt a lens more than a few degrees. Jamming of lens elements in their cells and edge chipping will almost never happen if the edges are slightly convexed. For aerial lenses, it is far more important for the reduction of vibration to achieve a tight fit in the cell by such means than to increase tolerances on diameters. As a fine point, the crown of the convexed edge should, if possible, lie in line with a plane through solid glass. In other words, a meniscus lens should be supported as nearly as possible by a plane through glass, rather than by a plane passing into the air space of the concavity. If this method is followed, a tight fit of the lens in the lens cell will not bend the lens appreciably.

In practice, it is rare that the quality of the instrument work matches the accuracy achieved by the optician. If instrument makers were permitted the same, slow, time-consuming lapping methods, no doubt their final accuracy would be as good. For the very best work it is desirable that cylindrical grinding be used extensively for the manufacture of accurate lens cells. In all such work with aerial lenses, the cell wall is likely to be too thin to support the strain of machine work within the close tolerances allowable. It is of the highest importance, therefore, that the instrument maker, or his foreman, design machine jigs to prevent any unnecessary stress or strain on the part in the course of machining, and to follow the machine work with a careful check of final accuracy.

The most frequent fault of the instrument maker is his failure to watch temperature effects on approaching final dimensions. Every gauge and standard requires periodic inspection and calibration. Inside measurements are much harder than outside measurements, primarily because the tip of the gauge must follow a saddle-shape contour in space. Care must be used to refer the inside measurements to a plane perpendicular to the optical axis. For the most careful work, plug gauges should be used. Such gauges should be as carefully standardized as the micrometers themselves, and should have slightly convexed edges to insure accuracy and freedom from jamming.

A most convenient way to check diameters objectively against standards is to use a dial gauge of the 0.0001-in. series. The spring pressure of the dial gauge insures that each worker will attain the same result, provided that careful attention is given to cleanliness, burrs, gauge lag, and to thermal effects. The dial gauge and accompanying stand also afford a convenient way for checking conical edges and ellipticity of supposed circular objects. Any handling of parts should always be accompa-

nied by alertness for thermal troubles caused thereby.

The subject of advanced cell and retainer ring designs is too lengthy for presentation here. Under the Harvard contract a prolonged attempt was made to improve on the methods of mounting and handling large lenses. Special attention was devoted to stabilizing and rustproofing the steel used in lens barrels and cells, in order to prevent change of shape or condition with time. The deep-freezing of steel was thought to be an absolute essential for success in prolonged service. It is believed that future efforts should be in the direction of stabilized, chemically blackened, stainless steel cells. The most promising alloy to date seems to be free-machining stainless 303.

In practice, it was unwise to trust the finished article of any worker unless check measurements could no longer be made. The completed lens system should be known to the assembler down to the last detail, if his job is to be carried out with assurance. All errors in diameter, parallelism of faces, ellipticity of parts, conical walls, and centering should be evaluated, and allowance made for them. Any jigs made up to achieve such accurate measurements are a saving of overall time and trouble.

By mechanical measurement alone it is possible for a skilled assembler to shim lenses and to handscrape metal faces until the assembled lens shows no faults of centering. The assembly process must be a cooperative one between instrument maker, opticians, assembly expert, and the optical designer. If one man can handle the entire job with meticulous care, so much the better.

The engineer should design the lens mounting, if possible, to permit adjustable but definitive axial positioning of lens elements. The best solution of this kind seems to be the spacer ring. Such a ring can be lapped and checked separately to the smallest tolerance required. These rings should also have slightly convex edges to prevent jamming. It is helpful to the assembler if small spanner holes are provided for extraction of separator rings in otherwise unreachable spots.

Metal fits produced by machining alone always seem tighter than the dial gauge or hand micrometer would indicate. The metal surface seems to contain myriads of small fibers that catch on one another in a close fit. For this reason convexing of close-fitting parts is essential if the finest accuracy is to be achieved. The depth of such convexing need be only one or two thousandths of an inch. Preferably, such tight-fitting parts should be cylindrically ground. Glass-to-metal fits can always be to closer tolerances than metal-to-metal.

Glass elements are most easily inserted in cells if handled by means of a vacuum chuck. It is important that the vacuum proceed either from a large vacuum reservoir, or from large pumping capacity. To protect coated surfaces, it is advisable to employ a single thickness of a soft material like Kleenex. The porosity of such a material makes a high pumping rate imperative for sake of safety. The rim of the vacuum chuck should be lined with a thin flexible ring like neoprene, and should be kept thoroughly clean. The crushing effect of the vacuum chuck often changes the dielectric properties of the nonreflective coat, so that a disfiguring layer of dust will tend to form on the ring where the chuck rim has rested. For this reason, the rim of the chuck should be very broad.

Normal centering methods were used on lenses smaller in diameter than 6 in. However, to replace visual methods, dial gauge indication was used on both surfaces of the lens simultaneously. After edging, the lens was not considered satisfactory until an accuracy of better than 0.0001 in. had been achieved on either side.

Among important methods developed under Contract OEMsr-474 were procedures for construction of precision concentric surfaces and very thin steep meniscus lenses. These procedures are described at length in the completion reports.

The final report[7] under Contract OEMsr-474 lists a number of points likely to benefit continuation or initiation of a new laboratory. Among the more important points is a strong recommendation for more general use of diamond methods in optical manufacture. The use of diamond tools was widespread in the American optical industry during World War II. It is believed, however, that such methods are

capable of considerable elaboration, especially for production of large size optical goods in quantity. There seems to be little reason why diamond milling cannot be employed on lenses up to 30 in. diameter with precision at least as good as obtained in standard practice on metal parts.

The chief task of the optician is the fine figuring of optical surfaces. It is advisable, therefore, to procure any labor-saving machinery that can permit him more time on the most important part of the work. It is entirely possible that diamond milling methods could produce a lens, already adequately centered and edged, and ready for the finest grinding.

In keeping with this suggestion is a strong recommendation to work out laboratory methods for quick manufacture of prototype lenses on an experimental basis. It would be wiser to construct a 7-element prototype lens in several days than to employ computers who tried for weeks to obtain comparable results by diffraction analysis and skew ray-tracing. It is unwise to construct an experimental model until the designer is certain that he is in the differential neighborhood of the desired result. Once near the final answer, however, it is possible for the designer to study the results obtained with a precision-made prototype on the optical bench and thereafter to decide what differential corrections are needed to obtain the final desired product. No amount of ray-tracing in a comparable time at comparable expense would give comparable results. It is no discredit to a designer if he resorts to such practical methods. It is more intelligent to use expedient methods than to emphasize one procedure at the expense of another.

It is to be expected, of course, that improvement in theoretical approach and in availability of electronic calculators will enable the designer to obtain ever better, more complex fundamental designs.

9.1.2 Quartz Monochromator

In connection with Navy research a specially made quartz monochromator was cemented and mounted under Contract OEMsr-474. Figure 1 shows a view of the final assembly.

The quartz monochromator consists of six segments of crystal quartz, all edged cylindrically to the same diameter, but varying in thickness geometrically by a ratio of two. Unit length of the quartz was so taken that the narrow bands of maximum transmission included both calcium and hydrogen wavelengths at 3,933 and 6,563A, respectively.

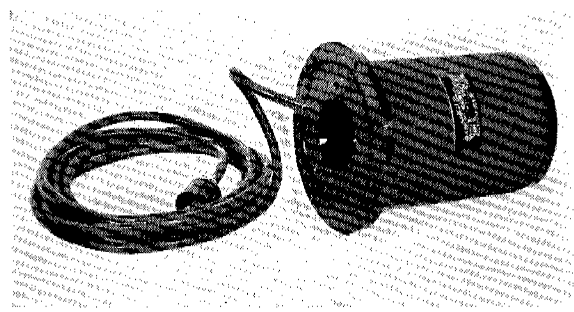

FIGURE 1. The quartz monochromator.

The NDRC portion of the work was primarily that of assembly. The quartz segments were received already finished to size. The monochromator requires a film of Polaroid to be cemented between each layer of quartz. Counting end segments of cover glass, there are seven films of Polaroid in all. Daily trips were made to the Polaroid Corporation for determination of the best orientation of each successive Polaroid film for maximum transmission at the required wavelength. Such a procedure guaranteed maximum efficiency of an otherwise rather inefficient kind of filter. The disadvantages for general purposes are more than made up by the 5-A wide filter band, ideally suited to study of the sun.

The unit length of the quartz filter was chosen to be of the required value at a temperature of 135 F. Slight heating in sunlight cannot therefore disturb the filter wavelength. Control of final operating wavelength and fine adjustment was provided by incorporating an adjustable thermostat and heating system into the mounting shown in Figure 1.

9.1.3 Paraboloidal Molds

In connection with other NDRC projects Contract OEMsr-474 was requested to manufacture

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in a matter of days a number of $f/0.5$ paraboloidal molds of 4 in. aperture. The molds were made of Pyrex glass with polished backs, sides, and bevels.

The parabolic curve required was transferred by draw filing and dial gauge measurement to a brass template. The average error of the gauge in aspheric depth was less than 0.0002 in. The molds were hand-finished to fit the gauge and tested under strong tangential illumination. Fine grinding was accomplished with handwork and flexible strips of metal. Polishing was accomplished on an automatic machine by use of very small diameter polishing buttons of pitch. The fact that the parabolic surface required had no inflection point made it possible with a full over-center stroke to achieve a very smooth overall result. Later tests at the Polaroid Corporation showed that several of the fourteen molds constructed were far better than the required tolerance of 0.025-mm image size at full aperture.

9.2 METHODS FOR MAKING ROOF PRISMS

9.2.1 Introduction

The production of optical parts in large quantities presents unique problems in many ways because of the high degree of precision required in the final product. In general, for the manufacture of such parts highly skilled workmen and specialized machines are required.

In June 1941, the Office of Scientific Research and Development, in anticipation of a possible future need for the rapid expansion of the facilities then existing for the production of roof prisms, initiated a Contract OEMsr-101 at the Mount Wilson Observatory of the Carnegie Institution of Washington for the investigation and development of new methods of roof prism manufacture. This program, carried out under Project AC-11, was to have as its primary goal the development of new production methods which did not require highly skilled workers, and which did not involve elaborate specially built equipment. Any new methods developed were to use, so far as possible, standard industrial machines.

9.2.2 General Principles of the Method Developed

The manufacturing procedure developed at the Observatory[8, 9] permits a division of the manufacture of roof prisms into two distinct stages. The end product of the first of these stages is a shaped and fine ground, but unpolished, roof prism of which the dimensions and the angles (with the exception of the roof angle) are established well within the required tolerances. Those surfaces, which need not be polished, require no further attention after this stage.

In the second stage of manufacture the prism faces are fine ground and polished, and the roof angle is corrected for each prism individually to bring it within the tolerance specified.

The process developed[b] for shaping the unpolished blanks makes use of a Blanchard No. 11 vertical-spindle grinder equipped with diamond grinding wheels and suitable jigs for holding the prism blanks. The grinder carries, for work on glass, a 10-in. cup wheel with a 1-in. face having a speed of 1,200 rpm. The table on which the work is placed is a magnetic chuck 16 in. in diameter which rotates at a rate of either 15, 24, 41, or 64 rpm. The chuck is mounted on ways, and may be withdrawn from under the wheel to facilitate loading. The spindle carrying the wheel can readily be adjusted so that its axis is parallel to that of the chuck. Over the center of the chuck passes the center of the 1-in. face of the grinding wheel. The motor drive is directly on the spindle, which may be raised or lowered rapidly by a torque motor, or adjusted accurately by hand. The downward feed is automatic, and takes place in steps, which occur 34 times per minute. The size of step is variable from 0.004 to 0.070 in., but the spacing in time cannot be changed. Coolant[c] is pumped from a tank in the base of the grinder

[b] The process to be discussed here was developed specifically for the Amici prism No. B 173131, of which 14,000 were milled at Mount Wilson for the Ordnance Department. It is clear that for the milling of other prisms slightly different jigs and slight changes in procedure would probably be required.

[c] The coolant consisted of a mixture of the solvent Quaker Cut No. 101 in water in the proportions of 1 gal of Quaker Cut to 80 or 100 gal of water.

and circulates out through the center of the wheel during the grinding process.

Several types of wheels for grinding (or milling) glass have been tested. Diamond wheels have proved to be the most satisfactory. Norton wheels of 100 grit and 180 grit have been used

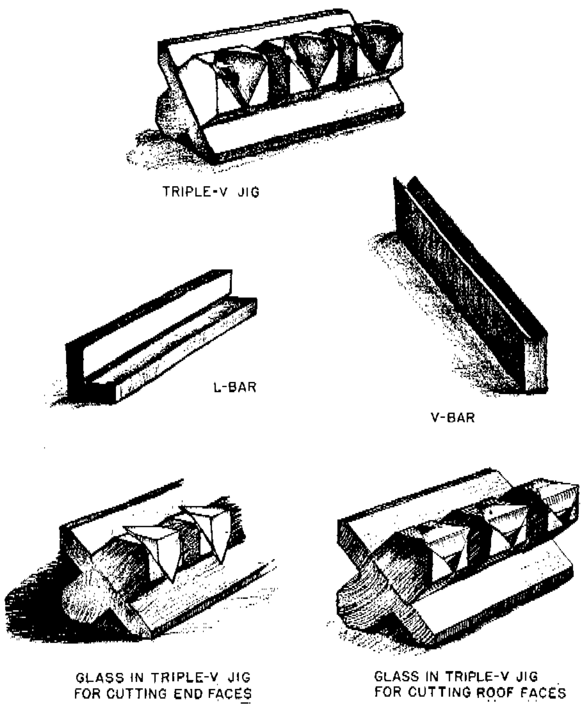


FIGURE 2. Jigs used in milling roof prism blanks.

regularly, and a wheel of 400 grit has been used occasionally. Of these the first is used for rapid cutting, the second with slower feed for finishing, and the third with very slow feed for producing a nearly polished surface. The bonding of the diamonds is metal for grits below 150, and Bakelite for grits above that number.

The accurate jigs used in the procedure developed represent one of the most important innovations of the process. It is through their use that the angles of the unpolished prism blanks can be established with the required degree of accuracy. Three types of jigs, illustrated in Figure 2, have been employed. The end faces and roof faces of the prism were milled with the triple-V jig, sides and bases with the V-bar jig, and tips with the L-bar jig. (For the nomenclature of the various faces of a prism see Figure 3, in which the dimensions and tolerances of prism B 173131 will also be found.)

The two defining surfaces of the triple-V jig, which rest on the surface of the chuck, are accurately lapped and ground to a 90-degree angle, with the aid of an autocollimator and two optical flats as illustrated in Figure 4. This angle defines the angle between the milled end faces (see bottom left of Figure 2), and also the angle between the two roof faces of the prism (see bottom right of Figure 2). Accuracy of the angle between the roof and end faces (the "angle of twist") is also important. This is controlled by the angle of the jig between the edges of the base on which the jig rests and the faces of the small V blocks in which the glass is fastened with wax during the milling process. The V blocks are made of hot-rolled steel. They are not hand-lapped as the bases are, but are ground accurately and checked with a precision square. They fit into a channel in the Meehanite base. The V blocks are shaped so that they give the maximum amount of support to the edge of the cut made during the milling of the roof faces.

The L-bar jigs are used for milling the prism tips. Each jig holds eleven prisms; six jigs are placed on the chuck at one time. The two legs are symmetrical, so that the setting of the machine for milling the first tip is also correct for milling the second tip.

Each of the V-bar jigs, used for milling the base and two sides of the prism, holds seven prism blanks placed in the V with roof faces down. The bottom of the V is generously relieved in order to avoid chipping the milled roof edge. The sides of the prisms are milled with the jigs lying flat on a special fixture shown in Figure 5. This is a circular magnetic plate which provides clearance for the glass which overhangs the sides of the jigs as indicated in Figure 6.

A necessary piece of auxiliary equipment for warming the jigs and prisms prior to waxing, and for removing the waxed prisms from the jigs following milling, was a Detrex degreaser of the type shown in Figure 7. Boiling trichloroethylene in the left-hand tank maintains an atmosphere of hot vapor up to the level of the water jacket. Here condensation occurs, and the freshly distilled solvent returns to the tank at the right. Two shelves (one within the vapor

and one above it) are provided for wire baskets in which jigs and prism blanks are placed. Any object lowered into the vapor is rapidly warmed and flushed by the condensation of the solvent put in groups of 400 to 2,000 for the sake of efficiency in handling and in order to avoid the continual resetting of the adjustments of the machine.

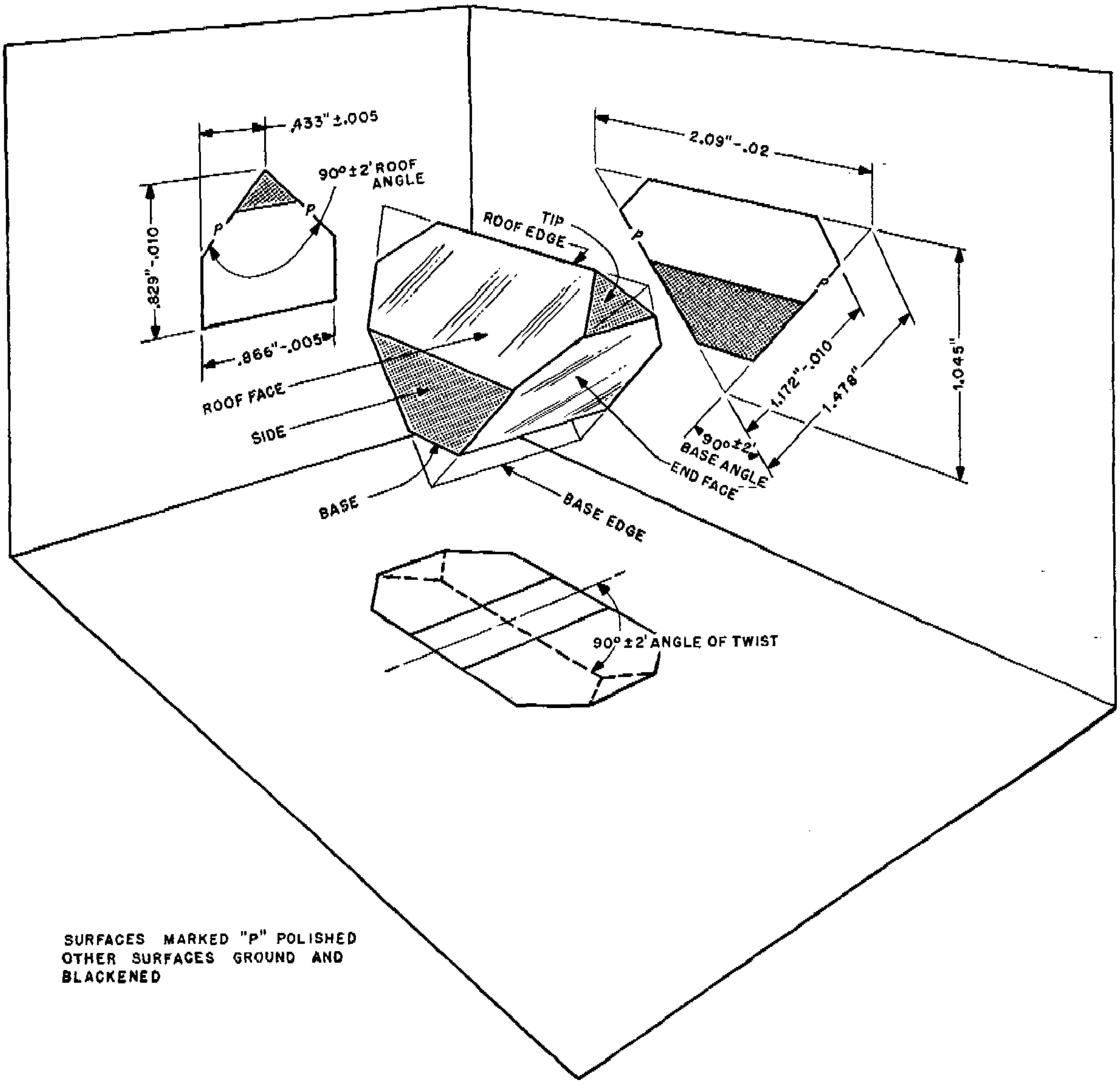


FIGURE 3. Roof angle prism dimensions and nomenclature.

upon it. Air is drawn off from the lip of the tank through the flue shown in the upper part of the figure. This was added to reduce the amount of vapor that escaped from the tank when the basket was removed.

9.2.3 The Milling Procedure

The milling procedure itself is divided into four operations, through which the prisms are

PREPARATION OF THE GLASS

Originally it was necessary to cut the rough blanks from large slabs of glass. A rapid method of accomplishing this with the aid of a diamond saw was devised.[8a]

In later work the glass was received in the form of pressings, known as Bureau of Standards pressed blanks, which have, roughly, the shape of roof prisms. About ⅛ in. of glass must be removed from each roof face and about ¼ in.

[redacted]

of glass from the ends of these blanks. Irregularities or ridges on the pressing frequently prevent them from fitting into the jigs properly

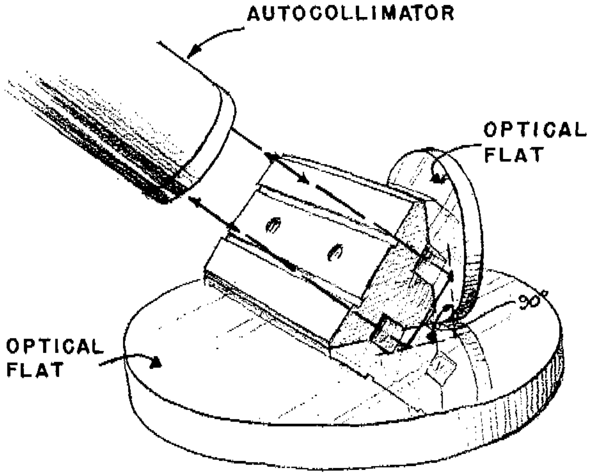


FIGURE 4. Optical testing of jigs.

for the first cut. They are therefore inspected and, if necessary, cleaned up before going to the milling room. This cleaning up is accomplished by rubbing the pressing across the surface of a rotating cast-iron plate covered with a coarse abrasive.

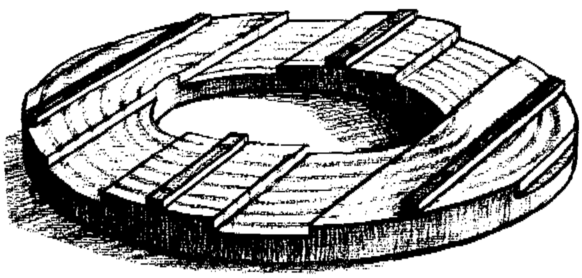


FIGURE 5. Circular magnetic plate used in milling sides.

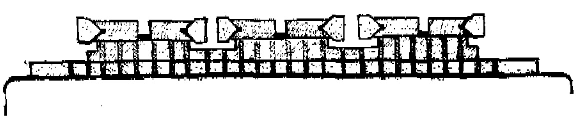


FIGURE 6. Section through chuck, plate, and V-bars.

OPERATION 1. MILL END FACES

A set of triple-V jigs, together with the proper number of prism blanks, are placed in a metal basket and warmed in the degreaser for about 20 sec in preparation for waxing. The heated jigs are transferred to a stand which holds them upright; the jig faces which come in contact with the glass pressings are wiped clean. Wax[d] is applied to the faces of the pressings which touch the jigs. Each prism is set into the jig, roof side downward (Figure 2, bottom left) and slipped endwise until it is approximately centered in the V block. After all

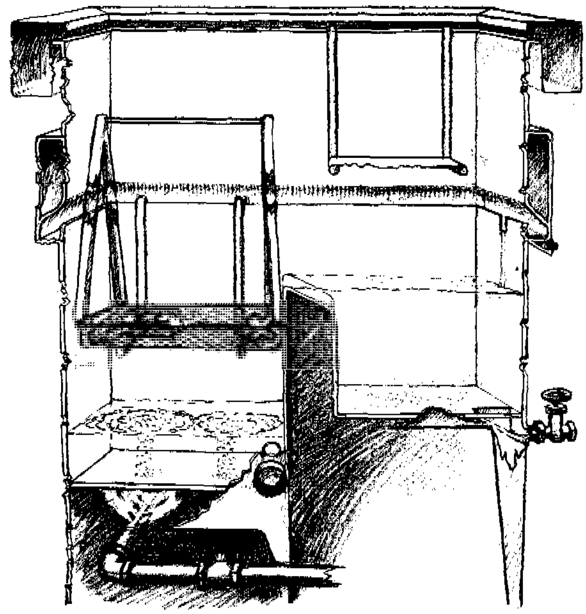


FIGURE 7. Interior of degreaser.

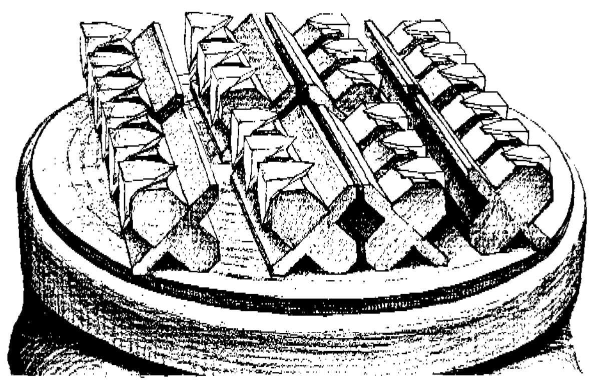


FIGURE 8. Triple-V jigs on chuck of grinder ready to cut end faces.

[d] The most satisfactory wax mixture to hold the blanks in place was found to consist of three parts beeswax, three parts rosin, and two parts Montan wax (by weight). This was much stronger than any other mixture tested. It melted easily, set quickly, and had a dark color. This latter property was an advantage during the waxing of a finished surface to the jigs or fixtures since it enabled the operator to detect readily any variation in thickness or contact by a change of color.

prisms are in place and the wax has set for a short period, the jigs are transferred to a cold table which hastens the completion of the setting. Since the pressings are rough, generous amounts of wax are used in this operation.

Eight jigs containing blanks are placed on the magnetic chuck of the Blanchard grinder (Figure 8) and the first face is milled. When this operation has been completed, the jigs are rotated 90 degrees about their longitudinal axis and the milling process is repeated for the second face. In this operation of milling the faces, two cuts are made on each face, one a roughing and the other a finishing cut.

The roughing cut is made with a 100-grit, 100-concentration metal-bonded wheel. The rate of feed for this first cut is usually about 0.070 in. per minute. At this speed there is some chipping, but this is not serious since most chips are cleaned up by the finishing cut, and all other faces of the prism still remain to be milled. About ¼ in. of glass must be removed from each face during this operation.

After the roughing cut has been made on both faces, the jigs are transferred to a second Blanchard grinder for a finishing cut with a 180-grit, 100-concentration resinoid-bonded wheel. The rate of feed for the finishing cut is from 0.016 to 0.028 in. per minute. About 0.020 in. of glass is removed during this finishing process.

The depth of cut is controlled by means of an indicator as illustrated in Figure 9. A small brass plate bridges the prisms, and the indicator is set by means of gauges calibrated to the various heights of the finished work above the chuck. These heights depend, of course, upon the dimensions of the jigs as well as on the prism specifications. The brass plate is placed under the gauge block and the indicator adjusted to read zero. As the cut progresses, the depth of glass remaining to be taken off is read directly on the indicator. Once the correct dimensions are reached, a zero point on the scale of the vertical feed can be established, and thereafter the grinding wheel can be stopped readily at the proper point without recourse to the indicator. The indicator dial method described need be used only occasionally, after the setting is once made, as a check on the wear of the grinding wheel and possible shifts in the adjustments.

When the blanks have been milled to the proper dimensions, the jigs and blanks are removed, put in a wire basket together with the next set of blanks to be milled, and placed in the vapor of the degreaser. In 15 to 20 sec the blanks become warm and slide off the jigs; within another 15 sec the wax is completely washed away. The basket is removed, the partially milled blanks are stored away, and the new pressings which were warmed in the degreaser are waxed to the jigs in preparation for milling.

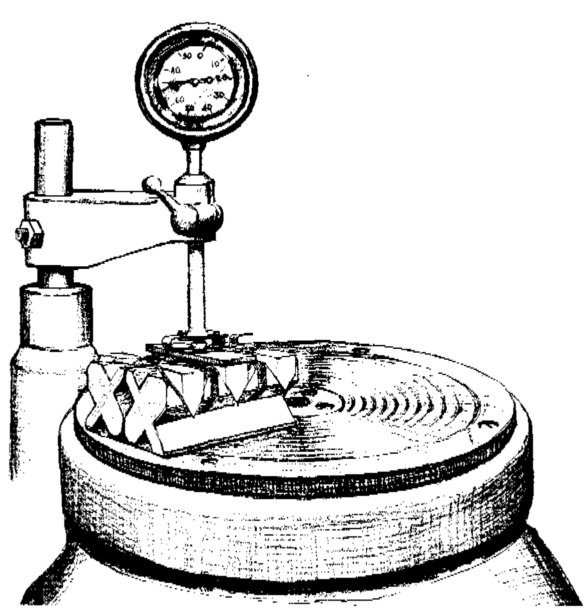


FIGURE 9. Indicator for establishing dimensions.

OPERATION 2. MILL ROOF FACES

When the end faces have been milled for the entire group of prisms, the second operation, that of milling the roof faces, is begun. The triple-V jigs are used once more, the blanks being waxed in them with the newly milled surfaces downward as illustrated in Figure 2, bottom right. Care must be exercised during this second milling operation because the roof edge and 45-degree end cuts are fragile and are easily chipped. A roughing and finishing cut are

generally taken as before,[e] although owing to the small amount of glass to be removed it would probably be equally efficient to make only one cut with the 180-grit wheel and thus avoid transferring the work from one machine to another.

When the milling of the roof faces has been completed, the prisms are removed from the jigs as before and stored until operation (3).

The roof cut determines the size of the prisms. After the milling of the roof faces, one or two prisms out of each group on the chuck are checked for dimensions from roof edge to base edge. In order to make this measurement, the prism is placed in a V block base down, and a smaller V block is placed over the roof. These are slipped under an indicator set for the proper dimension.

Operation 3. Mill Tips

The prism blanks, properly warmed in the degreaser, are next waxed to similarly warmed L-bar jigs, in preparation for milling of the prism tips. Six jigs, each carrying eleven prism blanks, are placed on the chuck. A cut having a depth of about $\frac{1}{4}$ in. is taken in the roughing and finishing operations. Since the edges may become slightly chipped, the finishing cut is made about 0.040 in. deep in order to remove these small defects.

Operation 4. Mill Base and Sides

The blanks are next waxed into V-bar jigs, roof-edge down as indicated in Figure 6, seven blanks to a jig. Ten jigs are placed on end on the chuck and the bases of the prisms are milled to the proper dimension.

A special magnetic plate of alternate steel and brass rings (see Figure 5) is then set on the magnetic chuck of the Blanchard grinder. Six V-bar jigs are placed on this plate (see Figure 6) and the sides of the prisms milled, 42 prisms being handled at a time. After the completion of the first side, the bars are turned over and the second side milled.

Since very little glass has to be removed from the sides, no roughing cut is made, and the entire operation is carried on with a 180-grit wheel. This operation completes the milling of the prisms. They are removed from the jigs, cleared, inspected, and packed for shipping, or are sent to the fine grinding and polishing department.

[e] The finishing cut in this second operation is usually rather deep in proportion to the roughing cut.

Operational Data

Routine milling of the type described in preceding paragraphs was generally carried out by two women operators, one doing the waxing and one operating the machines. One week of training was found sufficient for learning the waxing technique, and satisfactory skill in the routine operation of the machines could be gained in about a month. A supervisor spent about one-third of his time in the milling shop, much of this time being devoted to the improvement of the milling process and in the development of special equipment.

Table 1 gives data on 12 of the 16 runs during which 14,000 prisms were milled for the Army Ordnance Department. The first few runs show considerable fluctuation in the percentage yield and in the shop time per prism. The relatively poor results of run No. 1 may be attributed to inexperience and to the difficulties involved in getting the process started. In run No. 3 a silicon carbide wheel was used. It was found to be rather too hard and caused chipping. In runs No. 14 and No. 15 a more rigid inspection for chips was instituted and at the same time an attempt was made to speed up the process. The losses were reduced to a more reasonable level in the last run. In averaging the data, runs No. 1 and No. 3 have been omitted since it is believed that they were not typical.

The shop time per prism as given in the table, namely, 2.90 man-minutes, includes for each operation the time required for the entire process of waxing, milling, and removing the glass from the jigs. Those parts of the process which are not directly related to the use of machines are not included in the times given. Thus the hand-smoothing of blanks before the first waxing, the final inspection of the milled blanks, the packing for shipment (which require approximately $\frac{1}{3}$, $\frac{1}{6}$, and $\frac{1}{3}$ man-minutes per prism respectively) are not included in the entries of Table 1.

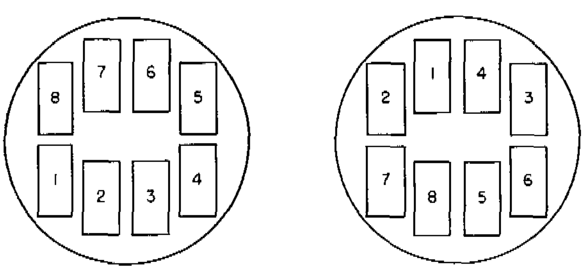
9.2.4 The Precision of the Milled Blanks

A rather extended series of milling runs was made in order to test the accuracy that could be expected of the roof angles, and to compare certain details of milling technique. Eight triple-V jigs, picked at random, were used in all the tests. The milling was carried out with the jigs at definite positions marked on the chuck. Three runs, called Series I, were made with the jigs in arrangement on the chuck as shown in Figure 10A. Three more runs, Series II, were made with the jigs in the positions shown in Figure 10B. A third set of three runs, Series III, was made with the jigs in the same positions as in Series I, but, in preparation for cutting the second face in Series III, a method of turning the jigs that was different from the method followed in the other series was used. In Series I and II the jigs were turned 90 degrees about the longitudinal axis as shown in Figure 11A. This procedure tends to cancel any errors in the alignment of the chuck. In Series III, illustrated in Figure 11B, the jigs were turned end for end, a procedure which tends to accentuate any error in the chuck.

In each run, the blanks were marked before removal from the jigs, so that the exact position of any blank during milling could thereafter be identified. The roof angles were all measured with a sensitive airflow gauge[9a] with which the roof angle could be determined readily and consistently with an accuracy of about 2 sec of arc. Each roof angle was measured at three positions: near each end and at the center of each blank. The reading along the vertex varied slightly. This variation was apparently caused primarily by a series of ridges or surface irregularities left by the grinding wheel. The ridges were approximately ¼ in. apart, and appeared to be an inevitable result of the fact that the wheel moves approximately this distance across the work each time it revolves.

TABLE 1. Operational data.

Run No.	Blanks processed	Per cent loss	Total shop time (hr)	Shop time per prism accepted (minutes) faces	roof	tips	sides and base	total
1	1,633	22.8	131.5					5.7
2	2,026	9.0	67.	0.54	0.67	0.41	0.57	2.19
3	1,690	16.0						
5	551	1.2	26.	0.72	0.99	0.39	0.77	2.87
6	578	1.9	25.25	0.75	0.78	0.45	0.69	2.67
7	551	2.3	22.5	0.69	0.75	0.35	0.61	2.40
11	551	4.4	24.	0.77	0.68	0.48	0.80	2.73
12	536	6.7	25.75	1.05	0.75	0.42	0.87	3.09
13	430	2.8	19.5	0.90	0.72	0.36	0.83	2.81
14	719	19.3	26.75	0.78	0.86	0.36	0.78	2.78
15	868	15.5	35.	0.90	0.78	0.49	0.70	2.87
16	2,106	3.1	157.5	1.37	1.69	0.76	0.77	4.59
Avg.	891	6.7	42.9	0.85	0.87	0.44	0.74	2.90



A SERIES I AND III B SERIES II

FIGURE 10. Arrangement of jigs on chuck.

In all, 648 roof-angle measurements were made which included three measurements of each prism, twenty-four prisms in each run (eight jigs each containing three prisms), three runs in each series, and three series. These constituted experiment A.

Following the completion of experiment A, the spindle carrying the grinding wheel was realigned and the surface of the chuck was ground as nearly flat as possible. The three series of test runs were then repeated. These new series formed experiment B.

In Figure 12, A and B, the distributions of

errors observed for the six series are exhibited. It is immediately evident that the errors in Series III are, on the average, considerably greater than those of Series I and II. This is not unexpected since it has already been pointed out that the method of turning the jigs employed in Series III accentuates any errors caused by misalignment of the chuck.

The departures of the roof angles from exactly 90 degrees may be traced to several sources of error, of which the most important are:

1. Errors in the alignment of the chuck and wheel, and lack of flatness of the chuck.
2. Errors in the jigs.
3. Irregular placing of the jigs on the chuck.
4. Lack of flatness of the milled surfaces.

The dispersion or scatter of the errors in any series can be ascribed primarily to irregular placing of the jigs and lack of flatness of the milled blanks, sources of errors that produce discrepancies of random size and sign. The average error of any series may be ascribed primarily to errors in the chuck and in the jigs. These are of the nature of constant errors. Assume, in the discussion, that errors in the jigs are independent of the state of the chuck and the method of turning the jigs, and that the error caused by the chuck is independent of the positions of the jigs on the chuck.

TABLE 2. Observed average error for each jig (sec).

Jig No.	Experiment A Ser. I, II	Experiment A Ser. III	Experiment B Ser. I, II	Experiment B Ser. III
1	15	42	1	— 8
2	17	31	4	0
3	11	30	— 3	— 5
4	1	27	—12	—25
5	15	46	— 1	—10
6	14	31	0	0
7	10	24	— 6	—11
8	25	45	6	—10

In Table 2 are listed the average errors of all the prisms milled in each jig during the various series.[f] Each of the numbers listed is essentially the sum of the error of the chuck and the peculiar error of the jig, the random errors caused by the irregular placing of the jigs, and the lack of flatness of the prism faces tending to cancel out. We may represent the error of the chuck during experiment A, Series I and II, by C_{A1}, during experiment A, Series III, by C_{A2}, during experiment B, Series I and II, by C_{B1}, and during experiment B, Series III, by C_{B2}. The peculiar error of jig i may be represented by J_i. The values of Table 2 may be represented

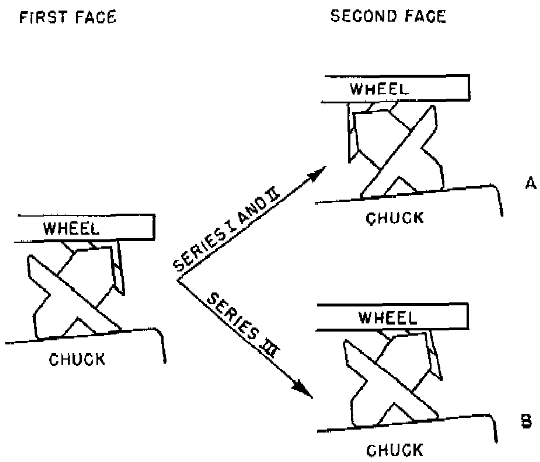


FIGURE 11. Methods of turning jigs.

by combinations of these errors. For jig 1, for example, we may write that

$$C_{A1} + J_1 = 15; C_{A2} + J_1 = 42;$$
$$C_{B1} + J_1 = 1; C_{B2} + J_1 = -8.$$

We can form from Table 2 thirty-two equations of the form shown above in twelve unknowns, four C's and eight J's. Unfortunately, the twelve normal equations derived from these by the methods of least squares are linearly dependent, and hence, being equivalent to only eleven independent equations, do not admit of a complete solution. In order to obtain numerical values for the C's and J's, we make the assumption that when the jigs are turned end for end, as in Series III, the constant error caused by the chuck is greater by some definite but unknown factor n than when the jigs are turned about a longitudinal axis as in Series I and II. This assumption leads to the two equations

$$nC_{A1} = C_{A2} \quad \text{and} \quad nC_{B1} = C_{B2}$$

which, combined with the equations in the C's

[f] In this table, Series I and II in each experiment have been combined for convenience in discussing the data. It is clear from Figure 11 that these series are very similar, although the dispersion of Series I is, in both experiments, somewhat greater than that of Series II.

[redacted]

and J's, give us thirteen equations in thirteen unknowns which can be evaluated. We find from a solution of these equations that:

$$\begin{array}{llllll} C_{A1} = & 11.1 \text{ sec} & J_1 = & 5.4 \text{ sec} & J_5 = & 5.4 \text{ sec} \\ C_{A2} = & 32.1 \text{ sec} & J_2 = & 5.9 \text{ sec} & J_6 = & 4.1 \text{ sec} \\ C_{B1} = & -\ 3.8 \text{ sec} & J_3 = & 1.1 \text{ sec} & J_7 = & -\ 2.9 \text{ sec} \\ C_{B2} = & -\ 11.0 \text{ sec} & J_4 = & -\ 9.4 \text{ sec} & J_8 = & 9.4 \text{ sec} \end{array}$$

$n = 2.89$ Average $J = \bar{J} = 2.4$ sec

Average deviation of J's $= \pm\ 5.9$ sec.

The error of the chuck, it will be noted, was overcorrected by the adjustments which were made after experiment A was completed, and the necessity of further adjustment is indicated.

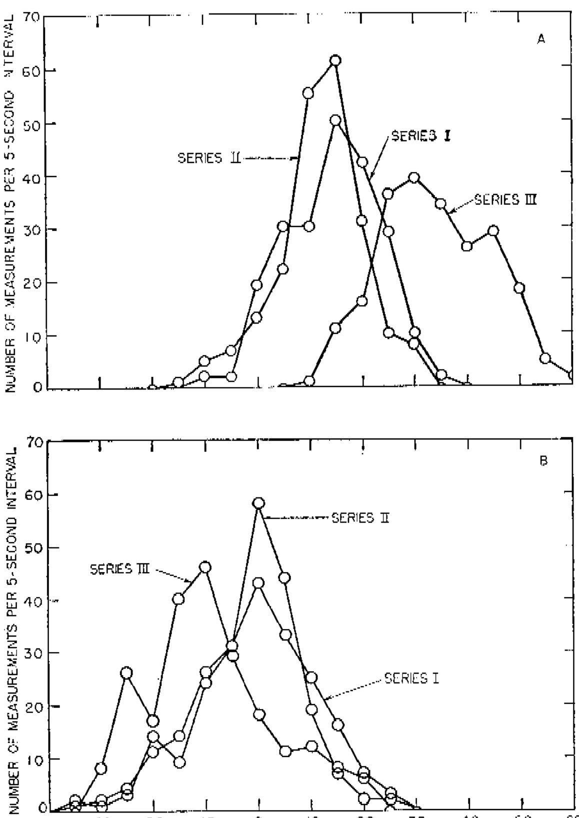


FIGURE 12. Distribution of angular errors. Experiment A, series I, II, and III. Experiment B, series I, II, and III.

The errors of the jigs are gratifyingly small. Before these experiments were carried out, the eight jigs tested and twenty-two others had been used in the milling of 17,000 prisms. Each jig had been through the waxing process about 375 times, and had been put on and taken off the chuck about 1,500 times. Such usage apparently has little tendency to distort a jig or to effect its accuracy.

The third source of error, irregularities in placing the jigs on the chuck, was investigated by forming for each jig the deviations of the individual runs from the average of the six runs of Series I and II. In Figure 13 the distribution curve of such deviations is exhibited. Experiments A and B are both included in the

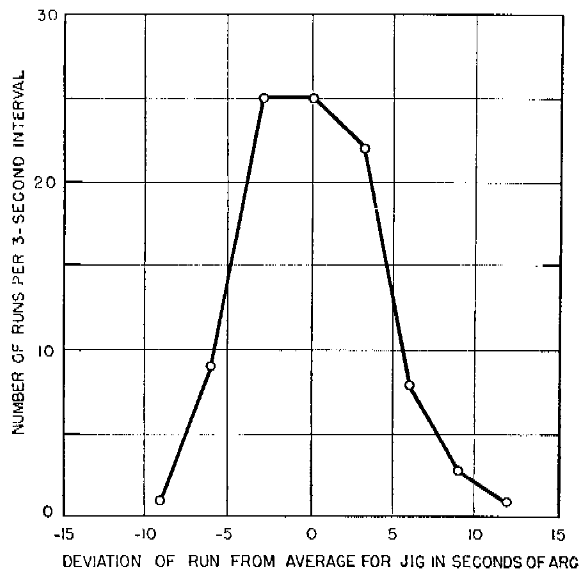


FIGURE 13. Distribution curve of deviations among individual prisms for each jig, which arise from irregular jig positioning.

results given, although the data from each experiment were treated separately in the calculations. The curve as derived must be regarded as providing an estimate of the upper limit of the effects to be expected from this source of error, for the points of the curve have not been freed completely from the effects of the other three sources of error. The indications are that any irregular positioning of the jigs on the chuck is of very minor importance.

The fourth source of error, nonuniformity of the milled surface itself, can be evaluated from a study of the scatter of the nine values of the angle determined for the prisms taken from one jig. The observed distribution curve for these errors is shown in Figure 14. The values on which the curve is based are independent of jig errors, chuck errors, and positioning er-

[redacted]

rors, provided these do not cause a warping of the jig. There appears to be a slight indication of the presence of such a warping, but it cannot be distinguished clearly from other causes of variation in the readings on one jig.

The dispersion in the errors caused by surface irregularities is large, and accounts for the greater part of the dispersion in the original distributions illustrated in Figure 12. The

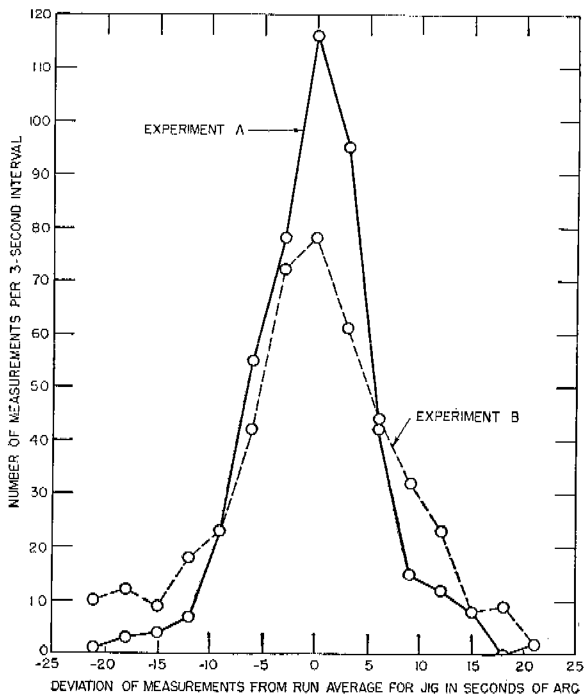


FIGURE 14. Distribution curve of deviations among individual readings for each jig, which arise from nonuniformity of the milled surface.

irregularities in the surfaces are due, as has already been pointed out, to the fact that the wheel moves an appreciable distance ($\frac{1}{4}$ to $\frac{1}{2}$ in.) during one of its revolutions. Since the periphery of the wheel can never be completely uniform, this motion results in a pattern of surface ridges on the face of the prism. Measurements indicate that these are from 10 to 25×10^{-6} in. deep.

These surface irregularities can be decreased in magnitude in several ways. From a practical point of view, however, their reduction is scarcely worth the effort required, for the methods of fine grinding and polishing now in general usage cannot take advantage of milling more accurate than that already attained in the process described. During fine grinding and polishing by the conventional methods of blocking the prisms in plaster, the milled angles are sometimes changed by as much as 30 sec of arc. In any finishing process in which errors of such magnitude are possible, it will always be necessary to correct each roof angle individually to keep it within the specified tolerance of 2 sec of arc. The dimensions and angles of the prism (aside from the roof angle) produced by the present milling process are of such a degree of accuracy that, in spite of errors introduced during blocking, no attention is required after the milling stage. All are well within the specified tolerances when the blank passes through the last milling operation.

9.2.5 Fine Grinding and Polishing

Although the work done at Mount Wilson Observatory was not primarily concerned with the finishing of roof prisms, valuable experience was gained from the work that was carried on in this field.

PREPARATION OF THE PRISM BLANKS

The Blocking Process. On a flat iron plate suitably coated with a thin layer of Kasson's waterproof grease, the prisms are laid out in a predetermined pattern, and a row of protective glass fillers is arranged on the plate around them. A flat $\frac{1}{16}$-in. thick brass ring is placed around the prisms and fillers, and on top of this is placed a steel reinforcing ring $\frac{3}{8}$ in. thick and 2 in. high. The thin brass ring serves only as a spacer, and is later removed. Wax (a 40-60 mixture of Montan wax and paraffin) is poured into the reinforcing ring until it forms a layer around the prisms $\frac{1}{8}$ in. thick. When the wax has hardened, plaster is poured into the mold formed by the reinforcing ring until the prisms are covered and the ring is completely filled. When the plaster has set, the block thus formed is slid off the iron plate, the spacer is removed, and the wax "etched" back with xylene to expose the faces of the prisms to be fine ground and polished. This grinding and polishing is carried out with the blocks face-down.

It has been found most efficient from the

point of view of minimum operator fatigue, size and type of processing machine used, etc., to make the blocks about 10 in. in diameter. The arrangement of the prisms within the block (each block carries 60 prisms) has been found to be of importance in determining the strength of the block and hence its tendency to warp and cause errors. Blocks with circular arrays of prisms were the most successful; those made with the prisms arranged in straight rows were unsatisfactory. For small prisms the practice of placing the prisms face to face in pairs was found to be particularly bad.

In the construction of the blocks, experience has demonstrated that grease is a more satisfactory temporary adhesive than wax, which tends to cause errors in the final polished prisms. For forming the block, ordinary "thirty-minute setting plaster" was found to be more suitable than various longer setting plaster mixtures. Blocks made up of pure plaster frequently have a tendency to warp; this was overcome by use of the relatively heavy reinforcing ring.

Fine Grinding. Fine grinding and polishing are carried out on identical machines.[9] Adequate control of the flatness of the prism surfaces is maintained during the fine-grinding process by means of a very simple and rugged air jet spherometer, operating on the same principle as the angle measuring device mentioned previously. By use of this instrument, departures from flatness or from a given spherical surface can be determined within two fringes.

The surface of a typical prism blank shows milling marks which have a visual depth of about 0.002 in., but which are, in fact, much deeper. In order to insure the removal of these fissures, it is customary to employ fine grinding to remove a layer of glass 0.005 in. thick from each surface to be polished. The time required to accomplish this is divided equally among three grinding stages, successively finer grades of milled natural garnet being used as the abrasive during the successive stages.

Fissures readily visible in the milled blanks may become completely invisible in a newly polished surface. They will later reappear, however, if the surface comes in contact with plaster during subsequent blockings. They will often be seen after the prisms have been cleaned in strong alkali or other liquid. Evidently, the sides of the cracks go into optical contact during polishing and appear later owing to the etching action of the alkali.

Polishing. Polishing and figuring are carried out with the block face down on polishing tools which are made of Swedish pitch loaded with ground walnut shell and tempered with pine tar, and which have a diameter about 20 per cent greater than that of the block being worked. Polishers made of such materials trim easily, do not scratch because of the soft surface layer which constantly works up from the body of the tool, and maintain their shape and serviceability for a very long period of time.

When finished, prism surfaces are given a coating of bituminous enamel for protection during subsequent blocking.

Roof Angle Corrections. When the two end faces and one roof face have been polished and figured, the roof angle is corrected. Two or three prisms are placed on each side of a contact block[g] (or "fence"), properly aligned with the aid of a jig, and gently pressed into optical contact.

In principle, the process of obtaining optical contact is very simple. Two perfectly clean, dry, and flat glass surfaces are gently pressed together; they will cling so firmly that they may be handled or worked as a solid piece. True optical contact is characterized by a complete lack of reflecting power at the contact surface.

Surfaces to be placed in optical contact must be absolutely clean; the slightest film of oil or speck of dust will effectively prevent contact. The surface may be cleaned by light rubbing with a cotton swab moistened with acetone to which a few drops of ammonia have been added to assure alkalinity, which is an aid in obtaining contact. The swab should not be dipped directly into the cleaning liquid. The liquid should be applied to the swab from a dropper in order to avoid contaminating the cleaner with oils from the cotton.

Another and better method of cleaning glass surfaces in preparation for obtaining optical contact is to rub them with a dry chamois pad which has been lightly impregnated with rouge. The use of such a rouge pad requires caution since continued or violent rubbing can seriously deform the surfaces. With proper care, however, a contact block can be cleaned fifty or more times and still remain serviceable. If the glass is sufficiently clean for contacting, moisture from the breath will condense in an even gray film over the surface. A streaked breath pattern indicates an oil film.

The rubbing of the surface of the glass during the

[g] These contact blocks have accurately plane surfaces which are parallel in the direction perpendicular to the edge of the block in contact with the polishing tool.

cleaning process generates a static charge which attracts particles of dust. The elimination of these particles is simplified by keeping the humidity of the room high, or by allowing rays from a quartz mercury lamp to fall upon the surface. Any particles of fluff or rouge from the pad may be removed with a small "gilder's tip" or camel's hair striping brush.

When the surfaces have been cleaned, the prism is placed *gently* on the contact block. If the surfaces have been properly prepared, the interference pattern first seen when the surfaces are brought together will settle down to a uniform gold color. In this condition the prism is not yet in optical contact; it can still be moved about slightly. The position of the prism on the contact block is corrected until the roof edge is in proper alignment with the edge of the block. When this adjustment has been made, a gentle pressure is applied to the prism until true optical contact is obtained.

The assembly of contact block and prisms is mounted in a cage, as illustrated in Figure 15, and the process of fine grinding and polishing is started. During this process the roof angle is corrected by proper weighting of the cage around its periphery. Convenient movable weights are provided for this purpose. The greater part of the necessary correction is made during the fine grinding.

For testing the roof angle, the cage is placed on three Stellite-faced spacers which define the plane of the roof faces being ground or polished. An autocollimating testing device is used to compare the direction of a beam of light reflected from the vertical face of the contact block (or "fence") and that of a beam of light reflected from an adjustable plane mirror mounted beside the cage. From the adjustment of the movable plane mirror and the relative positions of the two beams of light as viewed through the testing device, it is possible to measure the roof angle quickly, easily, and with a high degree of precision.

9.2.6 Conclusion

As a result of the experience gained in the manufacture of more than 18,000 shaped but unpolished roof prisms, it can be concluded that the process of diamond milling of roof prisms as developed at the Mount Wilson Observatory is highly successful. It appears that one milling plant of not very great size could supply enough blanks to keep in production all the optical shops in the country. For such a plant it would be worth while to introduce into the method described here certain refinements which would reduce the labor cost appreciably, but no essential changes in the process would be necessary. If the milling process were carried out on a commercial scale, it appears that the price for milling blanks would be approximately 50 cents per prism.

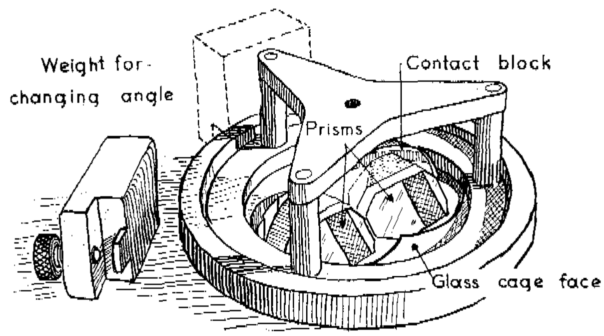


FIGURE 15. Cage for correcting roof prism angle.

In particular it should be pointed out that the accuracy of the blanks now produced by the milling process is as great as is warranted by the present fine-grinding and polishing technique. Before further improvements in the milling technique are attempted, improvements in the finishing technique should be made. If a finishing process which would maintain the accuracy of the milled blanks could be found (and such a development would be of fundamental importance to the optical industry) it seems very likely that roof prisms could be finished without being corrected individually for roof-angle errors, for it is very probable that improvements could be made which would permit the milling of blanks within the prescribed tolerances in angle. Primarily, these improvements would involve the generation of flatter surfaces. All other sources of error could very probably be kept within the necessary limit by close attention to details and without any fundamental changes in the milling technique which has been described.

9.3 GLASS MOLDING

9.3.1 Introduction

In its general search for optical production methods that would not require skilled optical

workers, the Office of Scientific Research and Development, under Project AC-11, entered into Contract OEMsr-421 with the Eastman Kodak Company in March 1942 for the investigation and perfection of methods of molding precision optical elements.[10, 11] It was felt that such a molding process, if it could be perfected, would be of use not only as a method for producing ordinary spherical optical elements, but would also make possible the mass production of aspherical elements such as Schmidt correcting plates and lenses with parabolic surfaces. The possibility of producing such aspherical elements in quantity would give the optical designer a new degree of freedom in his designs, and would enable him to improve the performance of many types of optical instruments.

9.3.2 Early Experimental Work: the Construction of the First Molding Press

The ordinary process of molding glass elements for use in roadside signs and similar devices involves the use of stainless steel molds. These are heated to a temperature of approximately 400 C and then used to press a piece of heated, plastic glass of suitable size and shape into an element of the desired form. The temperature of the glass in the plastic state is considerably higher than that of the molds, and a common fault of elements molded in air in the manner just described is the descriptively named "orange-peel surface" which results from the sudden uneven chilling of the outer layer of hot glass as it comes into contact with the relatively cool mold. Such an orange-peel surface, of course, makes the element useless in a precision optical instrument; Newton's rings are rarely, if ever, shown when a test glass is applied to an ordinary molded glass surface.

As a first step toward the elimination of this defect, the pressing must be carried out with the molds at a temperature approaching that of the plastic glass. At such temperatures, however, the glass sticks to the mold, and the mold rapidly oxidizes. A search was made, therefore, for metals to which glass would not stick when both glass and metal were very hot, and which, in addition, would not oxidize easily.

As the experiments progressed, it became apparent that, in order to prevent rapid oxidation and deterioration of the molds when used at temperatures of 600 to 700 C, it would be necessary to carry out the heating and molding process in an oxygen-free atmosphere. A simple experimental press, which is illustrated in Figure 16, was made up to determine the effects of some of the common inert gases on various metals and glasses heated to high temperatures. The operation of this press was very simple. The gas to be tested was admitted through the inlet at the bottom of the tube and it flowed

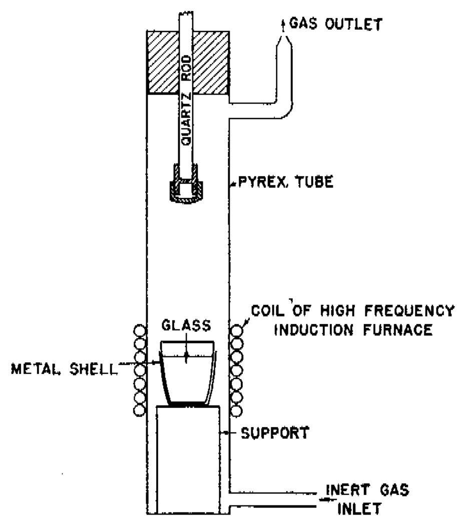


FIGURE 16. Experimental molding press.

through the outlet at the upper end of the tube. When the gas was flowing, glass in the crucible, which was surrounded by a metal shell, was heated by a high-frequency induction current. As the glass approached the plastic state, the mold on the end of the quartz rod was pushed down into the high-frequency field, heated to a temperature approximately equal to that of the glass, and then pushed down farther, until an impression was made in the plastic glass.

Commercial nitrogen, helium, and hydrogen, all freed from oxygen and water vapor by being passed over hot copper trimmings and calcium chloride, were tested in this device. Steel molds became dulled when heated to 600 C in nitrogen and helium. They remained bright, and showed

no tendency to stick to the glass, when heated in hydrogen.[h] Unfortunately, however, three types of glass tested in this press developed dark surface films when heated in hydrogen, owing to the reduction of the metallic oxides in the glass by the hydrogen. This surface darkening was only slightly noticeable when the glasses were heated in nitrogen.

The possibility was considered of constructing a press in which the glass, in pellets of approximately the correct size and shape, would be heated in an antechamber containing an atmosphere of nitrogen, transferred to a hydrogen-filled chamber where they would be pressed by the heated molds, and then be transferred to a second nitrogen-filled chamber for annealing. Many difficulties were encountered in the design of such an apparatus, particularly in the design of the various gas traps through which the glass was to be transferred from one chamber to another. The simpler, single-chamber press illustrated in Figures 17 and 18 was therefore constructed.

The essential details of this press are shown in Figure 18. Fundamentally, the apparatus consists of a pneumatic press having a 4-in. piston which moves the upper mold down upon the stationary lower mold. The downward travel of the piston is limited by an adjustable stop. Surrounding the molds is a gastight Pyrex glass envelope 42 mm in diameter and 250 mm long. Opposite the molds in this envelope is located a side port of 30 mm aperture extending about 35 mm out from the main envelope. Hydrogen[i] enters this envelope through two inlets and escapes through the side port where it is burned as it flows out into the open air. The flame very effectively prevents oxygen from entering the molding chamber. The molds, mounted on stainless steel tubes, are heated by a high-frequency induction current.

The glass to be molded in the press is used in the form of rods approximately 12 mm in diameter. One end of the rod is heated in a gas-fired muffle. When the tip of the rod is in the proper plastic condition, it is withdrawn from the muffle, passed through the hydrogen flame and the side port, placed between the molds, and squeezed by the press. As soon as the glass and mold cool below the yield point of

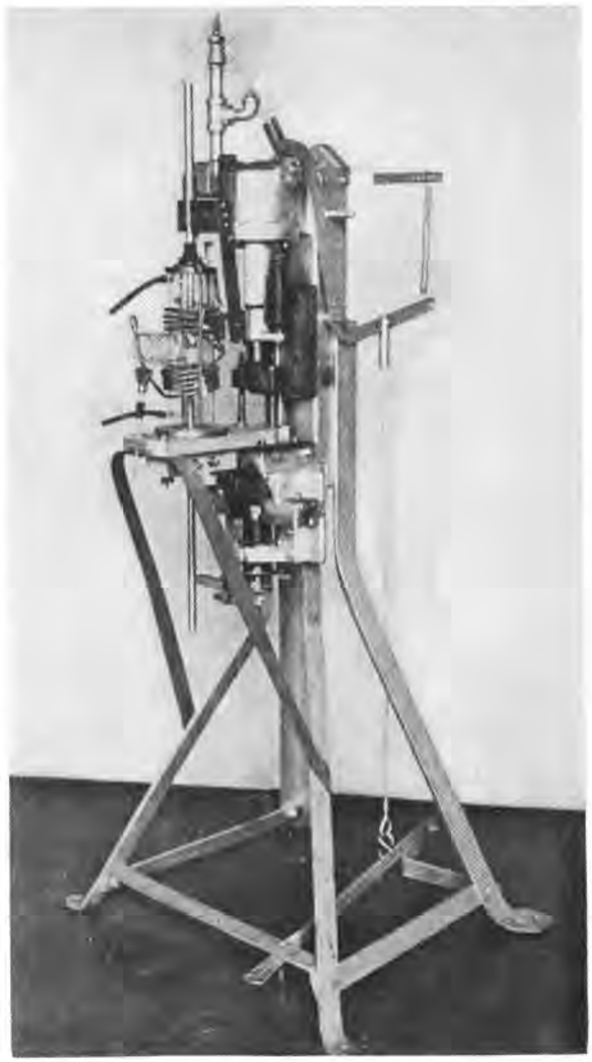


FIGURE 17. The first molding press.

the glass (a period of 10 to 15 sec is required for them to reach this point) the pressure exerted by the press on the glass is released, and the molded element is removed by means of the glass rod to which it is still attached.

Experience with this first working press has shown that:

1. Pure hydrogen is the most satisfactory

[h] The hydrogen was burned as it passed through the outlet into the open air.

[i] The hydrogen was purified by being passed through an iron tube filled with platinized asbestos maintained at a temperature of 700 C (which removed any oxygen present), and dried by being passed through a U tube filled with drierite (anhydrous $CaSO_4$).

[redacted]

gas for use in the molding chamber in spite of its tendency to darken the surface of some types of glass through reduction of their oxides. Various mixtures of nitrogen and hydrogen in the molding chamber have been tried in an effort to eliminate or reduce this surface

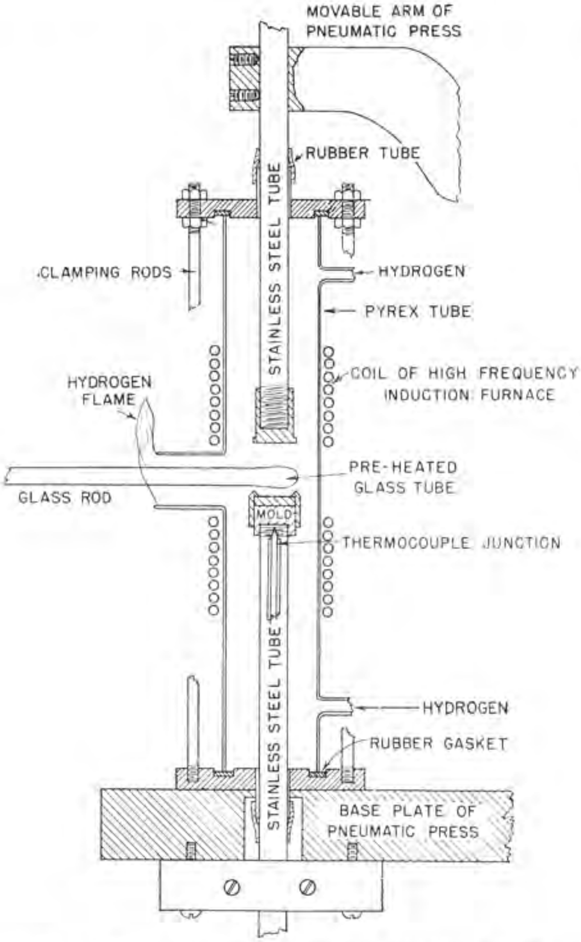


FIGURE 18. Section of the first molding press.

darkening, but the results have been unsatisfactory. When enough hydrogen is added to the nitrogen to make the mixture sufficiently reducing to maintain clean molds, and at the same time to make it sufficiently combustible to burn and form a flame seal at the side port, the mixture will also darken the glass, and so offers no advantages over pure hydrogen. Illuminating gas has been tried as an inert atmosphere, but has proved to be unsatisfactory.

2. It has been found that the pressure applied to the glass during molding can be varied within the range 150 to 300 psi without causing the glass to stick to the molds or affecting the properties of the finished element.

3. A safe working temperature for the molds has been found to be about 600 C when lime-soda and borosilicate glasses are molded, and a temperature of about 650 C has been found to be satisfactory when Pyrex glass is molded.

4. During the process of heating the glass in the gas-fired muffle in preparation for molding, the lime-soda and borosilicate crown glasses have a tendency to darken on the surface and thus to have their optical qualities impaired. This effect can be reduced by heating the glass in an electric oven. The darkening appears to be caused to a large extent by actual contact between glass and flame. Pyrex glass does not show this flame effect.

5. Stellite has been found to be the most satisfactory material for molds. It is very durable, it takes a high polish, and optical elements of high quality can be pressed with it. In Figure 19 is shown an example of the average quality of Newton's rings obtained with a $\frac{5}{8}$-in. diameter pressing formed by a Stellite mold with a plane surface. The figure of the glass surface is quite symmetrical, but is concave. The majority of

FIGURE 19. Newton's rings from Stellite molded plane surface.

the pressings made showed approximately the same concavity. In production, this systematic difference between pressing and mold could be corrected by the introduction of compensating

[redacted]

curvature in the mold, equal and opposite to that observed in the glass.

Stellite had the disadvantage that it was generally available in sheets at most 1/8 in. thick. It was finally supplied by the Haynes Stellite Company in the form of cast Stellite to which was welded a layer of rolled Stellite No. 6B. In making molds from these pieces, the molding surface was formed on the rolled Stellite.

Some stainless steels have also been used in the construction of satisfactory molds. Very generally, the stainless steels take a high polish; their durability, however, is critically dependent upon their exact composition. Experiments (which were carried on some time later than those on which conclusions 1 to 4 listed above were based) have shown that Stainless Steel No. 155 (machining type) is, next to Stellite, the most satisfactory material for molds that has been found.

From the point of view of durability, Armco ingot iron ranks very high among the mold materials tested. Unfortunately, it does not take a very high polish.

The question of suitable materials for molds was examined very carefully. A number of materials (chosen on the basis of a survey of 264 heat-resistant materials and a number of experiments) in addition to those already mentioned were tested.

Ordinary cold rolled steel rapidly deteriorated with use.

Platinum iridium (80 per cent Pt, 20 per cent Ir) was a satisfactory material, but was too expensive for general use.

No. 430 stainless steel took a good polish, but imperfections soon appeared on its surface and the mold rapidly deteriorated.

Monel metal No. 650 stainless took a good polish, but during the pressing copper was freed from the metal and the mold deteriorated.

Chromium plated steel (thickness of chromium 0.00075 in.) showed no tendency to stick to the glass, but after a few pressings had been made with it holes began to appear in the chromium and the mold became unusable.

Hawk-Eye stainless steel, used very successfully in the pressing of roadside sign lenses at temperatures of 400 C in air, deteriorated rapidly in pressing operations carried on at 600 C.

Nickel was too soft, and rapidly became flaky and crystalline, and produced a poor surface.

High-speed tool steel rapidly crinkled and completely lost its figure.

Tantulum tungsten carbide could not be polished satisfactorily.

The First Trial Production Test of the Molding Procedure

As a test of the press and the quality of optical element which could be produced with it, a trial production run was made on small reflectors for a Schmidt-type autocollimator designed at the University of Rochester and illustrated in Figure 20. Owing to the size of this element, it was necessary to enlarge the molding chamber and side port of the press.

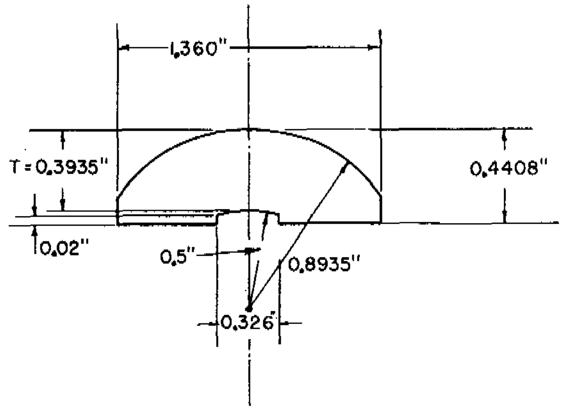


FIGURE 20. Schmidt reflector.

The side port in the revised model was provided with a stepped floor to eliminate back draft, and a fishtail air jet was placed below the port in order to produce a flat sheet of flame that would provide an efficient seal against the entry of oxygen into the molding chamber. These changes are illustrated in Figure 21. A new hydrogen purification system of large capacity was also provided for this enlarged chamber.

Nitrogen was made available for the purpose of flushing air out of the system before introducing the hydrogen. Hydrogen was then mixed with the nitrogen until the mixture would burn at the port. In this way the explosive backfires liable to occur, if pure hydrogen were ignited at the port, were prevented. After the flame was established, the nitrogen was turned off slowly until hydrogen alone was admitted to the chamber at the rate of 15 cu ft per hr. The molds were heated only while the hydrogen was passing through the chamber. After the molds had been allowed to cool, the flame was extinguished by admitting nitrogen to dilute the mixture.

Molds for the Schmidt reflector were made of Armco ingot iron according to the specifications shown in Figure 22. The small convex section of the plane mold shown in the upper part of

[redacted]

the figure was provided in the form of an adjustable insert so that by trial and error adjustment the press operator could correct any systematic distortion in the thickness of the pressing caused by differential effects between the hot mold and the glass.

Approximately 200 Schmidt reflectors were molded from Pyrex glass No. 774. They showed

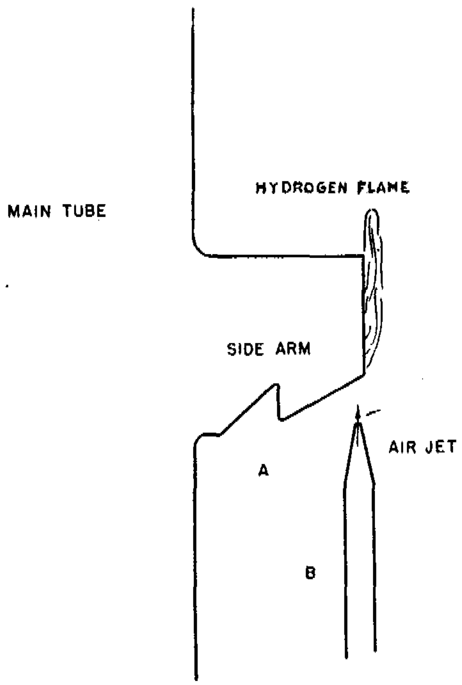


FIGURE 21. Section of glass-enclosed molding chamber.

very regular patterns of Newton's rings, but pits were always found in the molded surfaces. Since many of these pits occurred in fixed patterns, it is clear that they were caused by imperfections in the molds. The flat surfaces were less satisfactorily formed than the spherical surfaces. Shrinkage in the region of the small, indented spherical surface caused the flat portion of the reflector to be slightly depressed in the region surrounding the indentation. This depressed area could readily be corrected, however, by grinding and polishing the flat surface by rapid production methods, a procedure which in this particular case, would not be impractical.

There was a large variation in the thickness (the separation between the two spherical surfaces marked T in Figure 20) of the molded elements. Measurements of T for twenty reflectors (pressed consecutively) gave the distribution curve exhibited in Figure 23. The spread in T, from 0.415 in. to 0.427 in., is much larger than could be tolerated in elements of this type to be used in production.

Two reflectors of the correct thickness were selected and edged, and the optical quality of their spherical reflecting surfaces was tested. The performance of these surfaces, in spite of the pits which were present, were found to be satisfactory when compared with a standard instrument.

9.3.3 The Construction of the Improved Model II Molding Press

The variations in the thickness of the Schmidt reflectors appeared to be traceable, at least in part, to flexure in the frame and arms

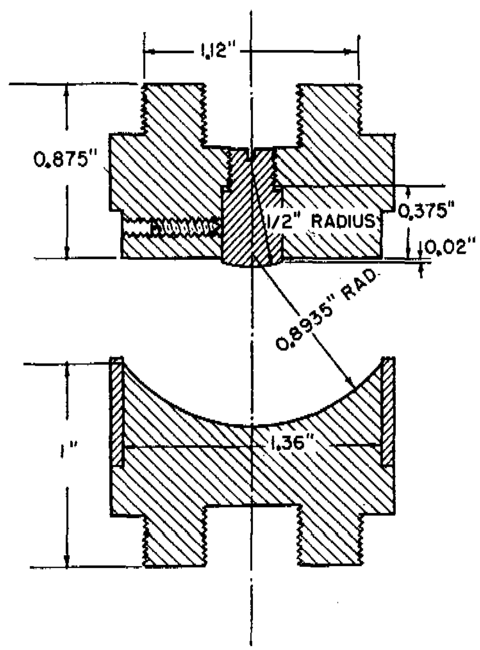


FIGURE 22. Section of molds for Schmidt reflector.

of the press. The actual amount of flexure of the press during any particular pressing operation was thought to be related to the volume of glass between the molds at that time. In order to eliminate this flexure in the frame and arms,

a new press, operating under the same general principles as the first press (Model I), but much more sturdily built than the first, was constructed as illustrated in Figure 24.

Molding chambers of several designs were tested during the construction of the Model II

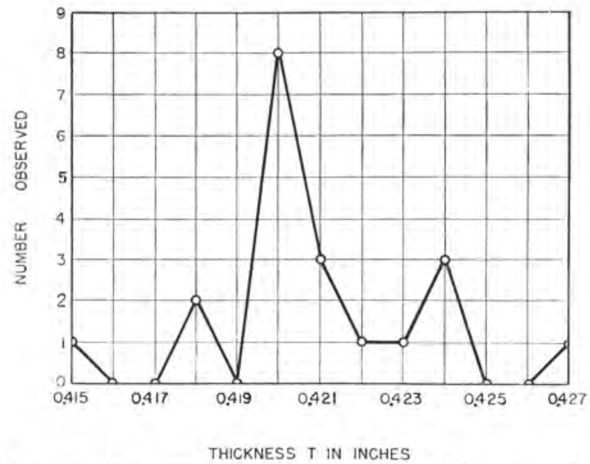


FIGURE 23. Distribution curve of thickness of Schmidt reflectors.

press. The chamber finally used was formed from a standard 3-in. Pyrex T-section pipe[j] with 1/4-in. thick walls. The chamber, fitted and mounted as shown in Figure 25, proved to be very satisfactory. It allowed good visibility of the glass being molded, it had ample strength to withstand any stresses to which it might be subjected, and it was large enough to allow elements up to 35 mm to be molded.

Because of the increased size of the molding chamber of Model II, high-frequency induction coils could not be placed sufficiently near to the molds to produce satisfactory heating. The molds were therefore heated by spirals of Nichrome V ribbon[k] placed just in back of them as shown in Figure 26. With a current of 40 amp at a potential of 6 v through these spirals, it was possible to heat the molds to a temperature of 600 C within a period of 10 to 15 min.

Hydrogen was admitted to the molding chamber of the Model II press through the stainless steel tubes carrying the molds and Nichrome heaters rather than through the walls of the chamber itself as in Model I. This new procedure has two advantages over the old: (1) It maintains a hydrogen atmosphere around the heating coils which therefore suffer very little deterioration. (2) The hydrogen, in passing through the tube, comes in contact with hot steel, and thus has removed from it, just before it comes in contact with the molds, any last trace of oxygen remaining after the regular purification treatment.

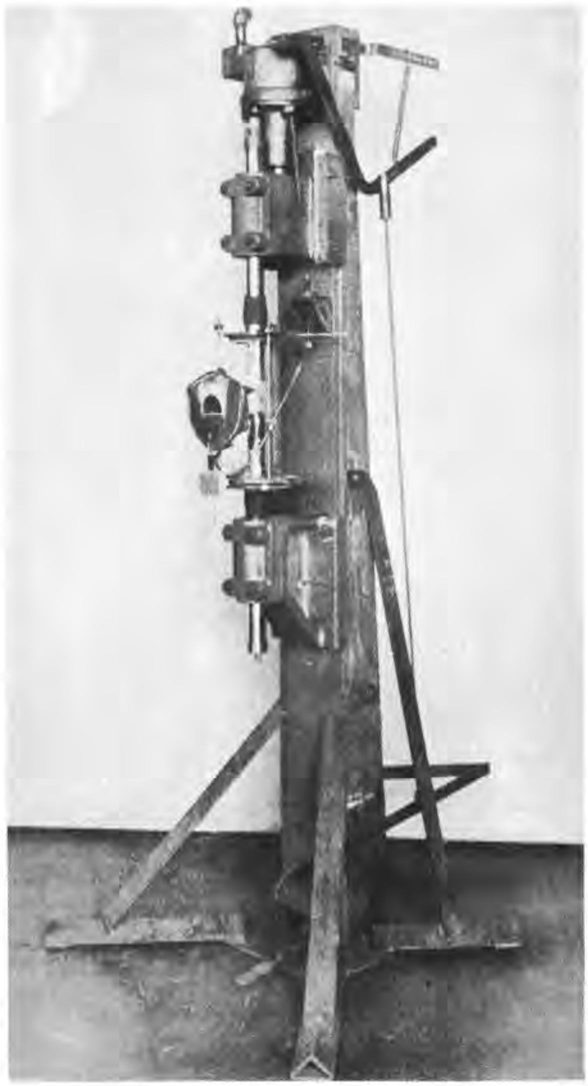


FIGURE 24. The Model II press.

The insertion of hot glass between the molds was found to increase their temperature to such a point that the glass had a tendency to

[j] The standard side arm of 5-in. length was reduced to 4-in. length in the construction of the chamber.

[k] The spirals were made up of 27-in. lengths of ribbon of dimensions 0.125x0.032 in.

stick to them unless the heating element was turned off during the actual pressing process. In order to prevent this sticking, a temperature regulation system, operating through a thermocouple of Chromel-Alumel mounted in

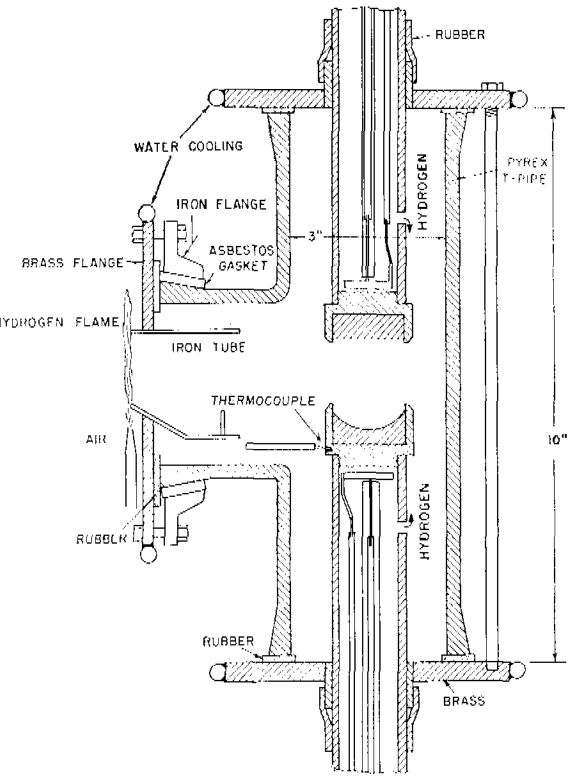


FIGURE 25. *Section of molding chamber for Model II press.*

the base of the lower fixed mold as shown in Figure 25, was installed. The regulator maintained the temperature of the molds to within ± 4 C when the press was idle. Within 2 to 5 sec after the insertion of hot glass between the molds the regulator would cut off the heater current which then remained off for a period 5 to 10 sec longer than the glass remained between the molds.

9.3.4 Experiments Performed With the Model II Press

SCHMIDT REFLECTORS

As a trial production run to test the method and apparatus, several hundred Schmidt reflectors (See Figure 28 E) were pressed from Pyrex glass No. 774 with molds made of No. 155 stainless steel. Two pressings, chosen at random as samples, and carefully inspected for optical quality, exhibited highly satisfactory spherical surfaces. They had no zones which departed from true figure by more than one-quarter wavelength. There were, however, a few scattered pits on the surfaces. These pits, viewed during the testing procedure as black dots on the brightly illuminated spherical surfaces, covered only a very small fraction of the total reflecting area.

About 150 Schmidt reflectors were pressed with Stellite molds made from the special welded blanks supplied by the Haynes Stellite Company. These Stellite molds produced sur-

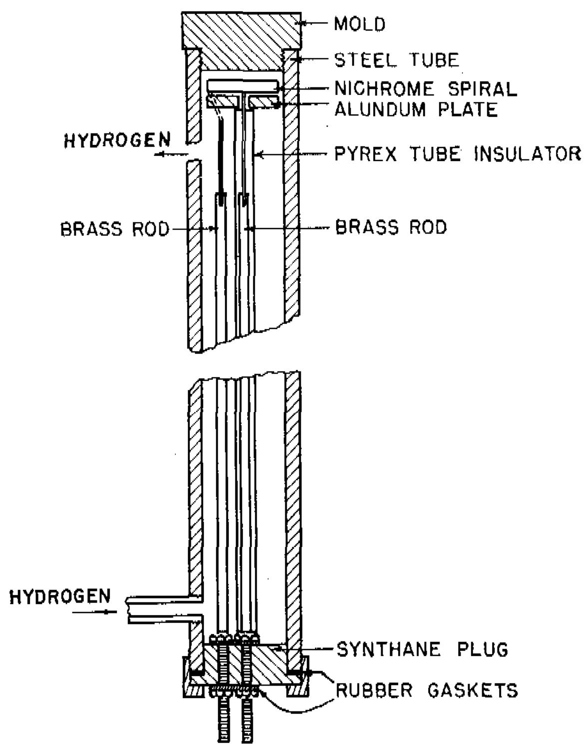


FIGURE 26. Section of resistance heater in tube.

faces of higher quality with fewer indentations than those pressed with the No. 155 stainless steel molds and showed less deterioration.

PLANE PLATES

Two series of trial production runs on plane-parallel plates pressed from blue cane (calcium-

sodium silicate) glass were made in order to test the quality and figure of molded flat surfaces. The first run, made with the molds illustrated in Figure 27, was unsatisfactory because of poor mold design. The thin rim of the lower mold cooled very quickly and caused a localized cooling and hardening of the glass which filled the lower mold. Thus, while the glass could be pressed into satisfactory contact with the relatively hot upper mold, it could not, at the same time, be pressed into contact with the relatively cool lower mold, and the pressings which resulted were of poor quality.

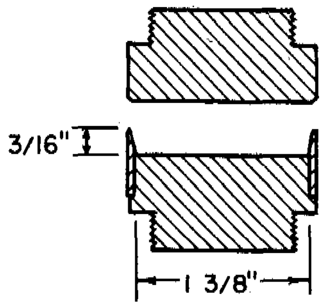


FIGURE 27. Section of plane molds.

It is probable that another somewhat similar effect is also operative here. As the hot glass is introduced into the molds by hand, there is a strong tendency to allow the glass to come in contact with the lower mold an instant before the upper mold is pressed down upon it. The lower portion of the glass is thus generally cooled more rapidly than the upper portion. The consequences of this situation (which probably exists for all molds) are similar to those just described for the thin rim alone. Probably both effects combined to cause the failure of the molds with the thin rim.

A second set of molds with a heavier rim was made from No. 155 stainless steel. These proved to be much more satisfactory than the thin rim set, although the glass did tend occasionally to grip the heavy rim. The two sides of a plate (illustrated in Figure 28) pressed with these molds tended to show different figures although the figures of both molding surfaces were the same. The figure of one side of the plate would not depart generally from the figure of the mold with which it was produced by more than one or two wavelengths; the figure of the other side of the plate would depart from the figure of its mold, however, by fifteen to thirty wavelengths. This effect, like the others which have been mentioned, undoubtedly arises from some phenomenon of unequal cooling.

A few pits were present in the surfaces of the majority of these flat molded plates.

Molds of Unusual Shape

In an effort to determine whether or not glass elements of unusual shape could be molded successfully, a mold 23 mm in diameter consisting of a flat plate with grooves of semicircular cross section across its face was constructed and tested. The glass (see Figure 28B) pressed with such a mold faithfully reproduced all the intricacies of the mold as nearly as could be determined.

Thickness Control

Measurements of the thickness of consecutive pressings made during the runs on the Schmidt reflectors and flat plates mentioned previously showed variations far greater than could be tolerated in production. The range of variation was similar in both series of measurements, and was approximately 0.04 in. The principal cause of these variations is the lack of control over the volume, and to a lesser extent, the shape of the mass of plastic glass inserted between the molds.

The Molding of Various Types of Glass

Pressings of some barium crown and borosilicate glasses (which were cast in the form of bars for use in the press) have been obtained with clear surfaces of reasonably good texture. Pressings of DBC-3 glass were very unsatisfactory because of the chemical reduction of the constituents of the glass which took place during the molding process. Tests with the Eastman rare-earth glasses were also very unsuccessful owing to the low viscosity of the glass at the softening point. It was impossible to soften the interior of a rod of rare-earth glass before the outer surface of the rod dripped off.

Production Tests

A production test of the Model II press was made at the Hawk-Eye Works of the Eastman Kodak Company. It was used to produce aspher-

[redacted]

ical lenses of 20 mm diameter and 41.6 mm focal length for use in the Mark 14 illuminated sight (the "Fly's-Eye sight"), which was developed by the Eastman Kodak Company under Division 7 of the NDRC.[12]

The mold for this aspherical lens was made of Stellite 6B, and was brought to the final proper figure by a series of zonal corrections. A number of pressings were made with the mold at each stage of its figuring. The pressed and finished lenses were measured for back focal length in a number of zones, and from these measurements the zonal corrections necessary to obtain a lens of the desired figure were computed and applied to the mold. By means of a series of such approximations a mold was finally produced which would form

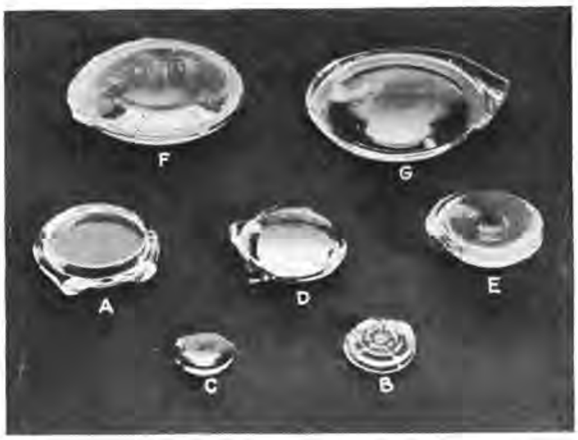


FIGURE 28. Molded elements.

aspherical lenses having the same back focal lengths for all zones.

The temperatures of the molds were automatically regulated. The upper (concave, aspherical) mold was maintained at a temperature of 500 C, the lower (flat) mold at a temperature of 400 C.[l] Blue cane glass was used for making the elements.

No effort to control the precise thickness or quality of the plane surface of the lens was made. These were taken care of by grinding and polishing the plane surface by conventional methods after the molding had been completed.

[l] The practice of maintaining the molds at different temperatures represents a slight departure from the molding techniques used in the experimental work.

The press was thus used to produce only the aspherical surface of the lens.

The quality of the lenses that have been produced by this method is very satisfactory; the figures of the aspherical surfaces varied from one lens to another by only one or two wavelengths. The yield of lenses judged on the criterion of definition alone has been approximately 90 per cent. The overall yield, however, in which rejections for material and surface imperfections are included, has been about 75 per cent.

9.3.5 A Model III Molding Press for Larger Elements

The limiting diameter of optical elements that could be produced in the Model II press was approximately 35 mm. In order to explore the problems involved in the molding of larger elements up to 50 mm in diameter, a new press designed generally after the pattern of the Model II press was constructed.

A photograph of the Model III press and its accessories is shown in Figure 29. The molding chamber was constructed from a standard 4-in. Pyrex T-section.

The primary point of difference between the Model II and Model III presses is the method of heating the molds. In the Model III press the heating of the molds is accomplished by high-frequency induction coils within the chamber and immediately surrounding the molds. The method of supporting the coils is shown in Figure 29. The extended tubes serve both as electrical leads and leads for water to cool the coils. Induction heating has proved to be very satisfactory; the molds are heated much more uniformly by high-frequency induction currents than by resistance heaters.

TESTS OF THE MODEL III PRESS

With the Model III press, a number of lenses (of blue cane glass) were made up from a plano-concave mold[m] having a diameter of 50 mm. From among the pressings produced (see Figure 28F, G), elements of high optical

[m] The concave mold has a radius of curvature of 50 mm. The molds were made of No. 155 stainless steel.

[redacted]

quality could be chosen. The general run of the lenses produced with the 50-mm molds, however, were very variable in quality, owing primarily to the lack of control of the amount, shape, and temperature of the glass inserted between the molds during the pressing.

There was no evidence of orange-peel surface on any of the elements. Depressions and irregularities in the surfaces of many of them were neither larger nor more numerous than those in the surfaces of the smaller elements.

The figures of the lens surfaces were regular, but some difference between the curvature of the lens surface, and the curvature of the mold which produced it, was usually observed for these larger elements. In production, this curvature effect could readily be compensated by a slight change in the curvature of the mold.

Two trial production runs were also made with plane molds of 50 mm diameter. Both Pyrex and blue cane glass were used for the pressings. The pressings made with the cane glass frequently fractured (because of their thinness) before they could be removed from the press. The general conclusions drawn from the run with Pyrex glass confirmed the conclusions drawn from the run made with the plano-concave mold.

9.3.6 Conclusions

A high yield of small lenses of satisfactory quality can, under certain limitations, be produced by the molding process which has been described. One of the central features of this process is the manual manipulation of a heated glass rod which is fed into the press. As the size of the element to be molded increases beyond 35 mm in diameter, the many uncontrolled variables involved in this manipulation begin to play increasingly important parts in the molding process. As these uncontrolled variables, such as the amount and shape of the glass inserted between the molds, the temperature of the glass at the instant of pressing, and the duration of pressing, begin to increase in importance, the operator begins to lose control of the molding process, and the yield of acceptable lenses begins to fall rapidly. This is particularly true when optical glass is used.

The problem of exercising sufficient control over the various factors involved in the molding process can be met with the introduction of various mechanical devices into the process. The perfected molding press must be constructed to perform in automatic sequence the following actions, possibly in different inert

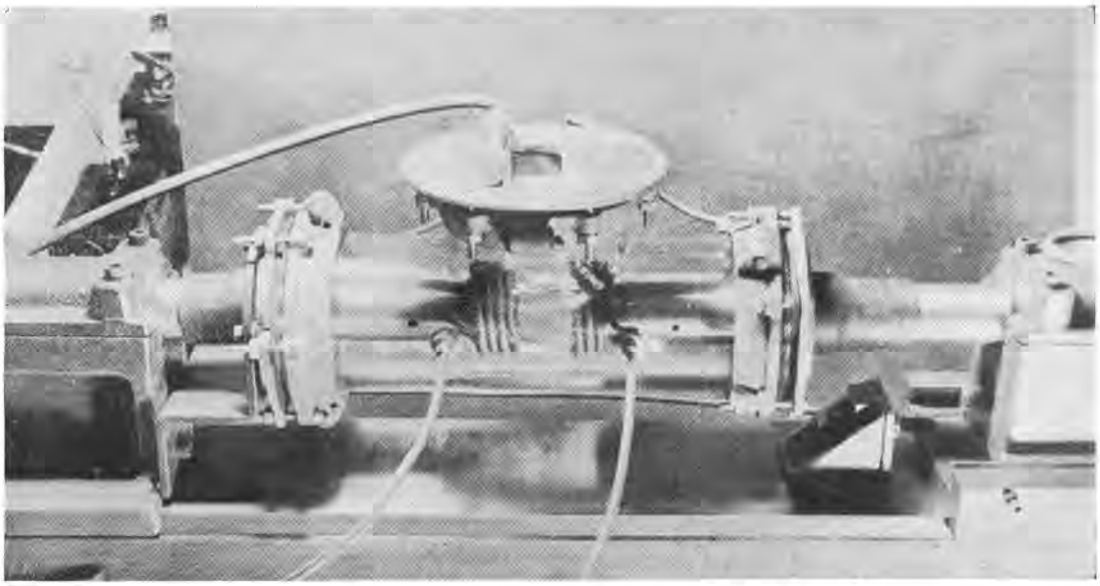


FIGURE 29. Molding chamber, right side, Model III press.

atmospheres: (1) Separate from the source of supply a stated amount of glass heated to the plastic state at the proper temperature either before or after separation; (2) Premold the stated amount of glass removed in the first operation so that the press will not be required to introduce a large change of shape in the plastic glass; (3) Insert the plastic preshaped slug between the molds, avoiding contact between the glass and the molds until the press acts to cause them to strike the glass simultaneously; (4) Release the molds at a stated temperature of the molded piece.

In the absence of such a completely automatic press, the process of molding optical elements, as far as its development has been described, is limited in its application by the following considerations:

1. The choice of glasses is restricted to types represented by blue and yellow cane glasses and Pyrex.
2. No precise control of the thickness of the molded piece is obtainable.
3. Only one satisfactory surface can be produced consistently.
4. A high yield of acceptable elements is obtainable for pressings up to 35 mm in diameter, and a progressively lower yield is obtained as the diameter increases beyond 35 mm. (The shape of the surface to be molded, however, is subject to wide variation without affecting the yield of acceptable elements.)
5. A small number of minute depressions and irregularities may be expected in the surfaces of the larger elements, but on the basis of the experience gained from the production of the Fly's-Eye aspherical lens, it is possible to eliminate these defects entirely in small lenses through those controls which can be exercised.

From the experimental evidence now available, it seems possible that a fully automatic machine which would employ the principle of molding elements in an inert atmosphere could, in time, be devised to perform the four automatic operations listed above on optical glass. With the perfection of such a machine, it would be possible to produce a molded element optically finished on both sides with either spherical or aspherical surfaces, and with thickness controlled within the usual optical tolerances.

9.4 METHODS FOR MAKING RETICLES

9.4.1 Introduction

During the period preceding America's entrance into World War II and for some time thereafter, the reticle situation in this country was very critical. The sudden enormous demand for such equipment made it appear doubtful whether or not facilities for reticle production by the conventional engraving-etching techniques could be developed rapidly enough to supply all needs. Moreover, the increasingly popular reflector-sight instruments (see Chapter 12) required at that time a new type of reticle for which satisfactory methods of production had not yet been worked out.

9.4.2 Photographic Methods of Making Reticles

One possible means of alleviating this critical situation, at least in part, was through the use of photographic methods of reticle production. It appeared, moreover, that photographic methods possessed a number of advantages not found in the customary engraving-etching procedures: (1) The reproduction of a complicated pattern would appear to require no more effort than a simple one. (2) There could be produced patterns containing features ordinarily difficult to achieve. (3) It should be possible to make more perfectly matched reticle pairs than had previously been produced. (4) It should be possible to produce sharper line edges than formerly. (5) The apparatus required for most photographic reproduction methods should be comparatively simple and inexpensive.

Research on photographic methods of reticle production was carried on at Edward Stern and Company, Inc.,[13] of Philadelphia (Contract OEMsr-293), and at the California Institute of Technology[14] (Contract OEMsr-389) under Service Directive NO-98. These laboratories had as their purpose under these contracts the testing of certain new photographic processes of reticle manufacture and the determination of the possible usefulness of those methods.

In all, six processes were tested. Four of these had been devised by the British Scientific Instrument Research Association, one was developed in the Eastman Kodak Research Laboratories, and one was developed at the California Institute of Technology [CIT] especially to meet the demand for reflex-sight reticles.

There are other photographic processes in operation which were not tested in these experiments. Two of these methods involve the production of the pattern by deposition of a metal through a mask or stencil produced on the glass by photographic means, and later removed. The quality of reproduction is excellent.

The Keuffel and Esser process, in its two modifications, is capable of producing reticles of high quality suitable for side illumination and scales with opaque lines, respectively. The permanence of the work is very satisfactory and the process has been used for production in limited quantity. It is not certain how adaptable it would be to the production of reticles in large quantities.

The Bausch and Lomb process produces reticles reasonably satisfactory for side illumination, but very fragile in character.

The Buckbee-Mears process of making metal reflex-sight reticles should also be mentioned. By this ingenious method, in which a pattern is photoetched through a thin metal sheet, a very durable and satisfactory reticle was produced in large quantities.

The General Bichromated Glue-Relief Process

This general process involves coating the reticle blank with a thin layer of bichromated glue and exposing it to light through a negative of the desired reticle. The exposed reticle blank is then washed in water, which removes the glue except from those places where it was affected by light. The glue remaining after this washing is made opaque by depositing in it dark material, and baked to increase its resistance to abrasion.

Variations. Methods of opaquing the glue include:

1. In the *British lead-sulfide* process, the glue forming the reticle lines is made opaque through impregnation with lead sulfide by alternate dipping in lead ferricyanide and ammonium sulfide solutions.

2. In the *Eastman glue-silver* process, silver is deposited in the glue relief and is built up to adequate density by repeated intensification through dipping in solutions of mercuric bromide, silver nitrate, and a developer.

3. The *British colloidal-silver* process involves the introduction of colloidal silver into the glue solution before the reticle blank is coated. This silver serves as a nucleus for intensification which is achieved through successive dipping of the washed reticle in solutions of mercuric chloride, silver nitrate, and metol-hydroquinone developer.

Methods Employing Etching of an Opaque Subcoat Under a Glue Resist

This general process involves providing the reticle blank with a subcoat of suitable opaque material before applying the film of bichromated glue. The glue is exposed to light through a *positive* of the reticle to be copied, and the unaffected glue subsequently washed away. The pattern is then developed in the subcoat by etching away those portions left uncovered by the glue resist.

Variations. Subcoat materials include:

1. The *British silver-line* process makes use of a subcoat of chemically deposited silver which is etched away with alcoholic ferric nitrate.

2. In the *CIT lead-sulfide-mirror* process, an opaque subcoat of lead sulfide is chemically deposited and subsequently etched with bromine, potassium bromide solution.

The Photoetching Method

In processes of this general type, the reticle is provided by photographic methods with an etching resistant material which is impermeable and resistant even to hydrofluoric acid. It is then etched with this acid, the resist is removed, and the lines are filled with some opaque material in the customary manner.

Variations. Etching processes include:

1. The *indirect* or *double-etching* process is essentially an extension of the preceding process. A pattern in silver is developed upon the

[redacted]

reticle surface, as in the British silver-line process, by etching a silver subcoat through a resist prepared with the use of photoengraving glue or other light-sensitive material. The silver pattern serves as the etching resist for the final etching with hydrofluoric acid.

2. The *direct* process is a method in which an etching resist is prepared directly by the use of a photosensitive resin which is resistant to hydrofluoric acid.

9.4.3 The Results of the Investigations

All phases of the methods tried and thought to be promising were thoroughly investigated. Considerable time was spent in a search for a suitable resist material for the direct process method, a subcoat material for the indirect-process method, and in the development of the lead-sulfide-mirror process. Several advances in the general technique of preparation of the master drawings and in the production of printing negatives were achieved.

In the overall view, all of the advantages hoped for in the photographic processes were not realized. In particular, it was found that the reproduction of a complicated pattern was more difficult than a simple one. Hand retouching was always required. The more complicated the pattern, the more time-consuming this became. Nevertheless, the photographic processes were still more rapid than the conventional mechanical methods. It was found that features difficult to produce by pantographic methods (especially patterns involving both narrow and wide lines) were also difficult to produce by photographic methods.

As to individual processes, the following conclusions were reached:

1. The bichromated glue-relief processes in general are simple, rapid, inexpensive, and suited to nearly automatic operation. The quality of reproduction is excellent, but the durability of the pattern is limited. Cleaning of the reticles, which are not generally suitable for night illumination, requires special care.

The British lead-sulfide process, one of the two procedures considered to show the most promise, is very rapid and convenient, but it has been found that the reproduction of lines much narrower than 0.001 in. may be inferior to that obtained with the Eastman glue-silver process and the British colloidal-silver process. Line opacity attainable with this process is limited, and lines free from scum are difficult to obtain. Reticles produced by this method are not suitable for use in reflex sights because of their insufficient resistance to heat.

The quality of reproduction obtained with the Eastman glue-silver process is excellent, and the line opacity very adequate. The method is applicable either to black-line or reflex-sight reticles. It is, however, more time-consuming than the British lead-sulfide process. It gave results superior to those obtained by the British colloidal-silver process.

In the British colloidal-silver process, intensification took place more rapidly than in the Eastman glue-silver process, but it was not possible to secure sufficient opacity to make the process applicable to reflex-sight reticles.

2. The British silver-line process is of very limited applicability owing to the inadequate adherence of the silver to the blank. It is not adapted to production of night-illuminated reticles; reflectivity of the silver makes the process unsuitable for reflex-sight reticles.

In the CIT lead-sulfide-mirror process, on the other hand, adherence of the sulfide coat is excellent. The coat is reasonably black; the reticles are reasonably permanent. They resist salt spray fairly well, and withstand moderate heat, but are considered insufficiently stable for use in reflex sights, in which the solar image may be focused on the reticle. The method is probably restricted in usefulness to opaque-field transparent-line work with lines not less than 0.002 in. wide.

3. In general, the photoetching method yields reticles of a permanent character suitable for night illumination. Excellent line quality may be attained under the best conditions. The percentage output of acceptable work, however, is probably smaller than that achieved with conventional pantograph methods. The process is far from automatic, and individual attention is required for each reticle, particularly in retouching pinholes in the resist. Resist materials developed so far have limited re-

sistance to hydrofluoric acid, the only satisfactory etching material, and hence there exists an upper limit to the line width which can be produced.

There are at present two resists of this type in actual use. The material developed at the Keuffel and Esser Company [K & E], and used there, has very limited resistivity, and, although it is adequate for the special K & E process, would be unsatisfactory for ordinary deep etching. The resist developed by Edward Stern and Company is probably the best so far devised. It appears to give a very clean-cut image by automatic development, and has given acceptable results with a deep-etching method. Its resistivity to hydrofluoric acid is none too great, however, and some trouble is experienced with pinholes which require considerable hand retouching before the final step.

The British photoetching process is complicated and involves many steps in each of which trouble may be experienced. While excellent results may be obtained, the yield of acceptable work may be small. Much depends on the skill and ingenuity of the personnel.

Of the processes tried, the British silver-line and the British colloidal-silver were found to have the most restricted applicability. The Eastman glue-silver process was compared with the British colloidal-silver process and found to be superior to it, but the former was not investigated extensively inasmuch as it was already being used successfully in production in the United States. Reticles produced by the CIT lead-sulfide-mirror process were superior in durability to some reflex-sight reticles which have been used, but were inferior to metal reticles developed by Buckbee Mears for the same purpose. The British lead-sulfide and the British photoetching processes were considered to be the most promising and were tested on a small pilot-plant scale.

In Table 3 estimates are given of the number of operator minutes to produce a reticle by each of the processes tested, and of the percentage yield of acceptable work.

In Table 4 will be found a comparison of line widths achieved by the three most promising methods. The pattern used for these comparisons consisted of a grid of lines of three widths denoted in the table by A, B, and C.

TABLE 3. Working times and yields of various photographic reticle processes.

	British lead-sulfide	British colloidal-silver	Eastman glue-silver	British silver-line	CIT lead-sulfide-mirror	British photo-etching
Operator minutes per reticle*	6	7	12½	7	10½	15-20
Percentage yield of acceptable work	60-70	60-70	50-70	60-70	60-80	20-30

* These times do not include periods during which the blanks were not actively handled in printing, baking, etc. They are based on processing in batches of six, and could therefore be reduced by handling larger batches in some of the steps, such as intensification and silvering.

In the photoetching process much time is consumed in cleaning, inspection, and spotting out. Presumably, this could be reduced with further work on the subcoat material. Rejects after the first etching of the silver subcoat may amount to 30 or 40 per cent. These may be turned back for reworking so that the blanks are not lost. In the Minneapolis Honeywell and Buckbee Mears plants, where reticles are produced essentially by this process, the completed work which is acceptable is said to average about 80 per cent.

Figures 30, 31, 33, and 34 exhibit the results of photographic processes, and illustrate some of their distinguishing characteristics. In Figures 33 and 34 a faint bulge is discernible at each T junction. This is characteristic of any photographic process in which the printing negatives are made by optical projection, and results from the limited resolving power of lenses. It can be avoided by making the negatives by some mechanical process.

In Figures 30 and 31 the horizontal base line appears to be slightly wider than the other lines. This is also discernible in the originals, but not to the extent visible in the plates, where it has been exaggerated by astigmatism in the microscope through which the photographs were taken. The widening is not due to any fault of the photographic reticle process, but to the difficulty of producing lines of constant

width in the master drawings. This irregularity in line width could undoubtedly be avoided through application of the skill and ingenuity gained with experience.

The beautiful clean-cut and crisp reproduction which is obtained by the glue-relief methods, and which is seldom, if ever, approached by any method involving deep etching, is illustrated in Figures 30 and 33.

Figures 32 and 35 show characteristics of average work in the process involving mechanical engraving of a wax resist and etching of the pattern so formed.

is being used in commercial production on a very considerable scale. From a practical point of view, it must be regarded as successful. It is likely that in certain special fields (for example in the production of rangefinder scales and reticles) the photographic methods have gained a firm position, but it is impossible to say to what extent they will displace pantographic methods. It is perhaps significant that in the Minneapolis Honeywell plant the two methods have been employed simultaneously.

TABLE 4. Line widths.

Process	Line widths (microns) ± Z*			Remarks†
	Line A	Line B	Line C	
Theoretical	16	23	45	assuming ideal reproduction of drawing
Eastman glue-silver	18	25	49	line quality acceptable
British lead-sulfide	20	26	50	line quality acceptable except that finest lines may show occasional defects
British Photoetching				
1. Silver resist (stencil)	15	23	47	
2. Etched line itself				
a. 4-sec vapor etch	17	25	29	line quality acceptable, filling unsatisfactory at crossovers
b. 8-sec vapor etch	20	27	53	line quality acceptable, filling satisfactory
c. 12-sec vapor etch	29	40	61	serious deterioration of line quality, rough edges

* Variation in line width ± Z microns.
† Crossovers were reasonably well produced in all cases.

9.4.4 Conclusions and Recommendations

It is difficult to make an objective comparison between the capabilities of mechanical and photographic methods. This difficulty arises in part from the fact that the methods of reticle inspection have not been completely objective, and as a result, the requirements have not been entirely uniform. One consequence of this is that a reticle process may be blamed for defects which existed in the original blank, and for which the process is not responsible. On the one hand, the photographic methods have not played as important a part in the reticle program as it was originally anticipated. On the other hand, reticles made by the lead-sulfide process and other methods giving equally fragile products are being used to some extent by the Services, and the photoetching process

In spite of the fact that they did not gain general acceptance during World War II, the photographic methods of reticle production are still attractive. Particularly so is the general method of directly producing an etching stencil on a surface which is light sensitive and at the same time resistant to hydrofluoric acid. It is highly probable that many resists exist which are far superior to any yet found, and that a search for such resists would be profitable. Such a search should be undertaken, it would appear, with the cooperation of a competent chemist experienced in the field of plastics.

9.5 LOW-REFLECTION AND HIGH-EFFICIENCY FILMS

In recent years great improvements in the performance of optical instruments have been made possible through the application of thin films of various materials to their optical elements. Through the use of such films on glass

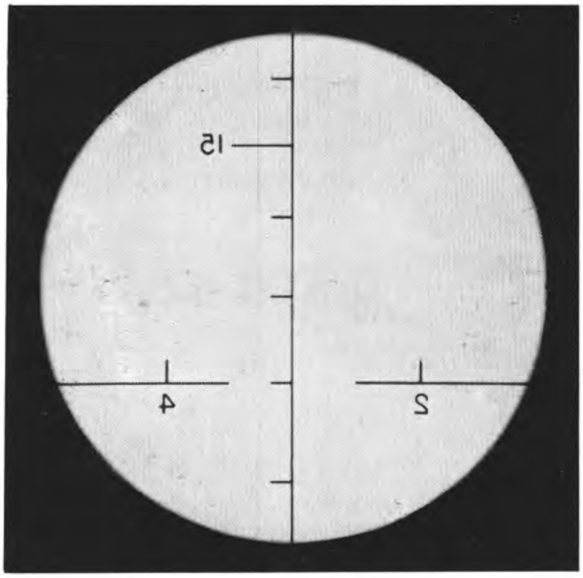


FIGURE 30. Eastman glue-silver process. (Enlargement is 17×.)

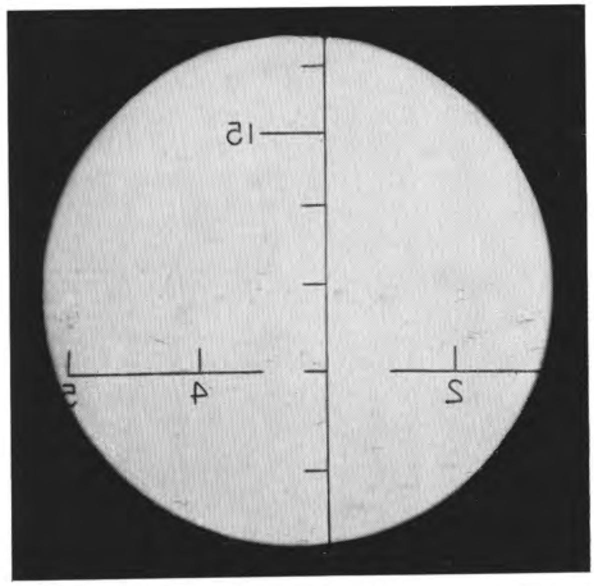


FIGURE 32. Reticle produced by pantograph. (Enlargement is 17×.) (Frankford Arsenal.)

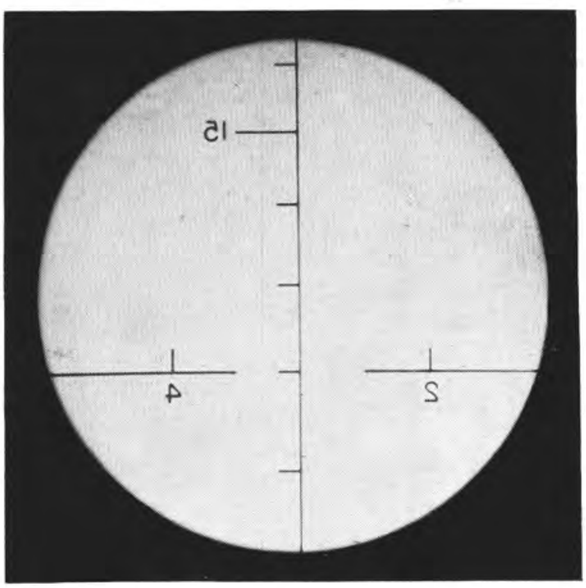


FIGURE 31. Photoetched reticle. (Enlargement is 17×.)

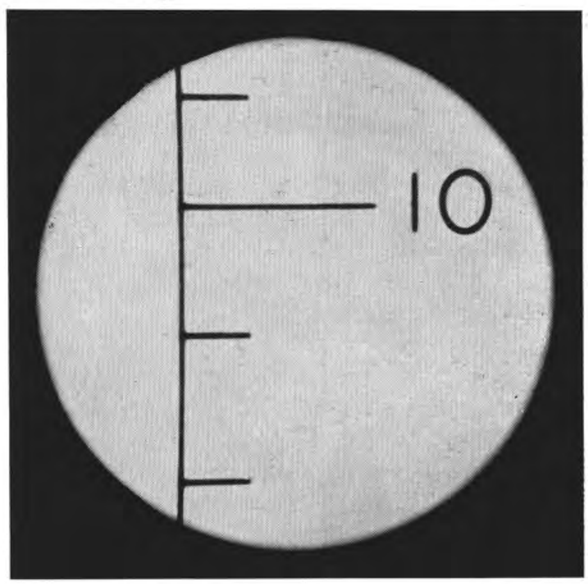


FIGURE 33. Eastman glue-silver process. (Enlargement is 56×.)

it is possible to decrease or increase surface reflection, to make polarizing beam splitters, neutral filters, and so forth. In view of the general importance and the numerous applications of such films, research on various aspects of their development was carried on by the Office of Scientific Research and Development under Project AC-11 and CE-27, through research contracts with the California Institute of Technology[15] (Contract NDCrc-118), Vard, Inc.[16] (Contract OEMsr-529), and the University of Rochester[17] (Contract OEMsr-160).

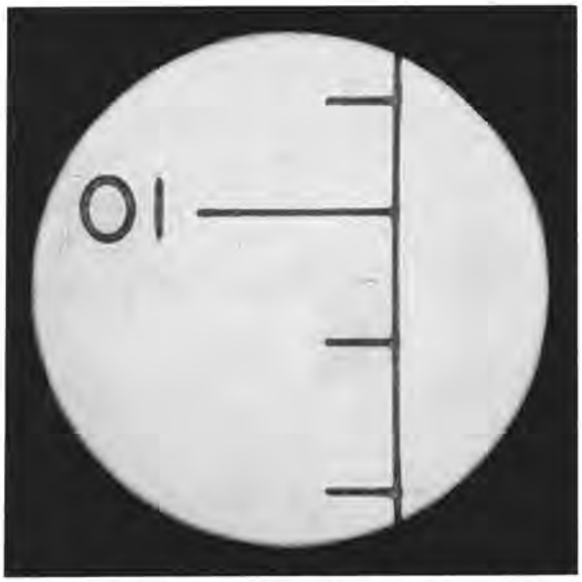


FIGURE 34. Photoetched reticle. (Enlargement is 56×.)

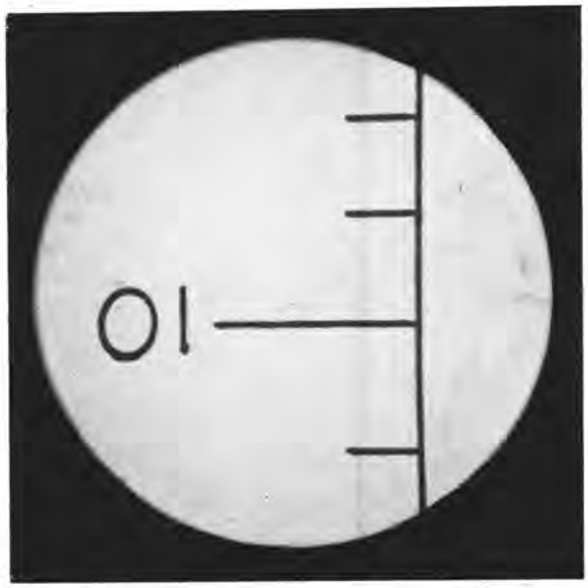


FIGURE 35. Reticle produced by pantograph. (Enlargement is 56×.) (Frankford Arsenal.)

9.5.1 Low-Reflection Films

No doubt the most widespread and best known application of thin films to optical instruments has been in the reduction of reflections from lens surfaces. While the amount of light lost by reflection from the two surfaces of a single lens is not ordinarily large from most points of view, the amount of light lost through air-glass reflections in an optical instrument, in general, rapidly becomes large as the number of optical elements is increased. In Table 5 are tabulated the percentages of light transmitted by instruments containing various numbers of optical elements. It is apparent from an inspection of these data that great difficulty would be experienced in using under conditions of poor illumination an instrument containing ten or more optical elements. This difficulty of obtaining sufficient light intensity for clear visibility because of loss of light through surface reflections in the optical instrument can, to a large extent, be eliminated by coating the lenses with films of the proper material and of the proper thickness, as may be seen from Table 5.

SIMPLE THEORY OF LOW-REFLECTION FILMS

In Figure 36 is represented a glass surface coated with a thin film. The index of refraction of the glass (at wavelength λ) we represent by $n_{g\lambda}$. The index of refraction of the dielectric material forming the film we represent by $n_{f\lambda}$, which we stipulate must be less than $n_{g\lambda}$. The index of air we take as unity. The arrows A and B represent beams of light reflected normally from the air-film surface and the film-glass interface, respectively.

From Fresnel's law of reflection we can write that the amplitude $r_{A\lambda}$, of light of wave-

[redacted]

length λ reflected from the air-film surface, is given by the equation

$$r_{A\lambda} = \frac{n_{f\lambda} - 1}{n_{f\lambda} + 1}.$$

Likewise, the amplitude $r_{B\lambda}$, of light of wavelength λ reflected from the film-glass interface is given by

$$r_{B\lambda} = \frac{n_{g\lambda} - n_{f\lambda}}{n_{g\lambda} + n_{f\lambda}}.$$

If none of the light in the beam entering the instrument is to be lost through backward reflection, we must arrange conditions so that the two reflected[u] beams A and B interfere with

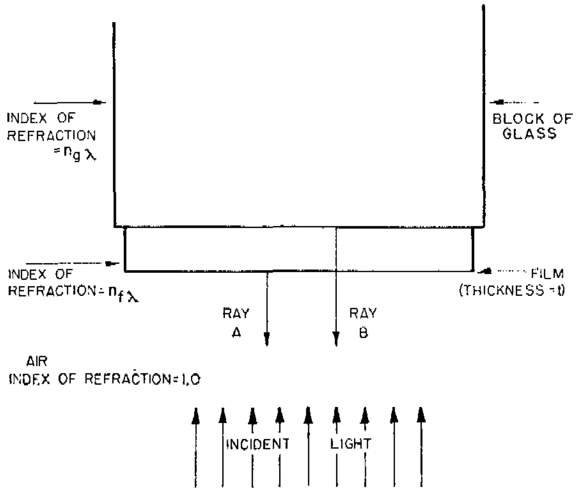


FIGURE 36. Rays of light reflected normally from two surfaces of a thin film on glass.

each other destructively. For this interference to take place, the two reflected beams must be out of phase, and must have equal amplitudes. Thus

$$n_{f\lambda} t = \frac{1}{4}\lambda,$$

where t represents the thickness of the film, and

$$\frac{n_{f\lambda} - 1}{n_{f\lambda} + 1} = \frac{n_{g\lambda} - n_{f\lambda}}{n_{g\lambda} + n_{f\lambda}}.$$

From these equations we find that

$$t = \frac{\lambda}{4} \cdot \frac{1}{n_{f\lambda}}$$

and,

$$n_{f\lambda} = \sqrt{n_{g\lambda}}\,.$$

Inasmuch as the wavelength and index of refraction appear in these expressions, it is clear that complete elimination of reflection can be accomplished for only one wavelength of light. Partial elimination of reflection, however, will be accomplished for a band of wavelengths of considerable width on either side of the wavelength of zero reflectivity.

[u] Multiple reflections are neglected in this brief summary. Investigation shows that the essential results of this discussion are not altered by their inclusion.

TABLE 5. Light transmission of an optical instrument containing various numbers of optical elements (calculated).

Number of optical elements	Overall transmission (per cent) uncoated	coated	Relative increase (per cent)
1	92.0	99	7.6
2	84.5	98	16.0
3	78.0	97	24.3
4	71.6	96	35.5
5	66.0	95	44.0
6	60.5	94	55.5
7	55.7	93	67.0
8	51.3	92	79.5
9	47.2	91	93.0
10	45.5	90	100.0
20	21.6	81	279.0

At angles of incidence other than normal, the theory of reflection becomes more complicated. Polarization effects must be considered, and the index requirements of the materials of which the films are made become more stringent. It can easily be shown that in the case of low-reflection films for oblique rays the thickness of the film may be determined from the equation

$$t = \frac{t_0}{\cos r_\lambda},$$

where t_0 is the thickness of film for zero angle of incidence, and r_λ is the angle of refraction of a ray (of wavelength λ) in the film. This angle can be computed by means of the expression

$$\frac{\sin i}{n_{f\lambda}} = \sin r_\lambda,$$

i being the angle of incidence of the ray under discussion. If the film is to be nonreflecting for a ray striking the film at an angle of incidence i, the index of refraction of the material of which the film is formed must be related to the index of refraction of the glass $n_{g\lambda}$, through the equation

$$\left(1 - \frac{\sin^2 i}{n_{f\lambda}^2}\right)^2 = \left(1 - \sin^2 i\right)\left(1 - \frac{\sin^2 i}{n_{g\lambda}^2}\right).$$

If we choose $n_{g\lambda} = 1.51$, then for

$$i = 0°, n_{f\lambda} = 1.23$$
$$i = 45°, n_{f\lambda} = 1.15$$
$$i = 90°, n_{f\lambda} = 1.00.$$

Several methods of producing films having the properties required for the elimination of reflections have been tried: (1) Dilute solutions of various acids have been used to dissolve out certain of the metallic oxides from a thin surface layer of the glass treated. A porous layer of silica is thus formed; air enters the cavities in the silica and a film of index of refraction effectively lower than that of the glass proper results. (2) Very thin layers of various materials have been applied to glass by a dipping process. Layers of the required thickness of one-quarter wavelength[o] can be built up by successive dipping. A variation of the dipping method involves spinning the film onto the glass surface by means of a rotating device. (3) Thin films of various metallic salts have been deposited on glass by evaporation in a vacuum chamber.

The first of these methods, while apparently offering a very permanent treatment, does not produce effective low-reflection films on all types of glass. It involves, moreover, a very special technique for its successful application, and, in addition, the lenses to be treated require special handling during manufacture and after treatment. The method has never achieved great popularity.

The process of spinning a film onto a lens has been used to some extent commercially and by the Services, but the film thus formed is less efficient in eliminating reflections and has poorer mechanical properties than that produced by the evaporation process. This latter process, from the point of view of efficiency of film produced and adaptability to quantity production is, so far, the most satisfactory process known.

Among the various materials (generally alkali metal and alkali earth fluorides) used in the evaporation process to form the film, magnesium fluoride, calcium fluoride, cryolite (Na_3AlF_6), and chiolite ($2NaF{\cdot}AlF_3$) have proved to be the most useful and practical. Cryolite is the material most used in Europe. Each of these materials has certain advantages and disadvantages. Films made from calcium fluoride are very efficient, but, unfortunately, are very easily damaged. Films of magnesium fluoride have better mechanical properties but poorer optical properties than films of calcium fluoride, and so forth. Among the primary objectives of the research on low-reflection films carried out by NDRC have been the improvement of the efficiency of the films in preventing reflection and the increase of their resistance to abrasion, sea water, and so forth.

In the search for more efficient films many new materials, mainly silicofluorides and fluorides containing two metals, were tested. None of these were found to be superior to the materials already in use; most of them were, in fact, inferior.

Two lines of attack on the problem of the improvement of the mechanical properties of the films were followed. The first of these was one originally suggested by Cartwright and Taylor in U. S. Patent No. 2,207,656, where it is stated that over a fluoride film (which had purposely been made a little less than one-quarter wavelength thick) might be deposited a very thin protective layer of quartz or zircon. A search was made for materials that had the protective properties of quartz or zircon, but were more suitable for easy evaporation in a vacuum chamber. While no such materials that were completely satisfactory were found, there was an indication that very thin coats of certain metals evaporated onto the fluoride film might be changed into hard transparent protective oxide coats when exposed to the atmosphere. From the experiments performed, however, it was not possible to arrive at a definite conclusion as to the true merits of such a procedure.

The second general line of attack on the problem of hardening the fluoride film and of improving its mechanical properties in general involved bombardment of the film with ions in a partial vacuum, treatment by mechanical rubbing, treatment with heat, and combinations of these. Different types of films reacted differently to the various treatments. In general, it

[o] In this discussion optical thickness will always be understood unless it is specifically stated otherwise.

[redacted]

was possible to find a technique of treating any film so that its mechanical properties would be improved and its optical properties would not be harmed at all, or only slightly.

The process which appears to be the most satisfactory for producing low-reflection films of average efficiency in eliminating reflections and of good mechanical properties is one developed at the Naval Gun Factory and also investigated by NDRC. The procedure involves a heat treatment and the use of specially purified magnesium fluoride in an evaporation process. Before evaporation of the fluoride, the optical elements in the evaporating chamber are heated to a temperature of approximately 200 C by irradiation from Nichrome wires. When they reach this temperature, the fluoride is evaporated. The coated elements are then baked at a temperature of 200 C for a period of approximately 1 hour. Films treated in this manner show no structure even under a magnification of 15,000×, are unharmed by immersion in concentrated nitric acid for a period of 12 hr, show no effects when subjected to salt spray for 1,000 hr (they do show some deterioration after 1,500 hr exposure), and are not affected by distilled water over long periods of time. Such films reduce the amount of white light reflected from glass of index of refraction 1.7 from 6.7 per cent to approximately 0.5 per cent, and for glass of index of refraction 1.52 from 4.2 per cent to approximately 1.4 per cent.

Cryolite, deposited on glass treated in the manner described, does not form a film so hard or insoluble as magnesium fluoride, but there is some indication that the cryolite is more efficient in reducing reflection. This reflection reduction factor depends greatly upon the index of the film, which is very sensitive to the vacuum conditions at the time of evaporation. The higher the pressure at the time of evaporation, the greater the reflection reduction factor, but, unfortunately, the softer and less resistant the film deposited.

The Evaporator and the Evaporation Process

The evaporators used in the formation of low-reflection and other films are now so generally well known because of the widespread usage of coated optics by the Services that no detailed description of the apparatus with which the greater part of the work discussed in this report was done will be given. Only its main differences from conventional evaporators will be pointed out.

The apparatus used in these experiments was designed primarily for research, but it was also found to be highly satisfactory as production equipment. Its chief point of departure from a conventional evaporator is that, instead of consisting essentially of a glass or metal bell jar resting on a metal base plate, it was made in the form of a cylinder from a piece of drawn brass tubing 12 in. in diameter, and closed at the bottom by a soldered brass plate. On the top of the cylinder, a shoulder was constructed with provision for a lightly greased soft-rubber gasket on which could be placed a flat 14-in. disk made of heat-treated Libby-Owens Ford ¾-in. glass which formed the top of the tank. Atmospheric pressure on the outside of this glass plate was sufficient to seal it as soon as the fore pump in the vacuum system was turned on. This plate could very quickly and easily be cleaned after each evaporation. The apparatus as a whole was very easy to clean, and this constituted one of its greatest advantages over the conventional type of evaporator.

The main pump lead and the filament leads come in through the side of the cylinder rather than through its base. Valves in the vacuum lines are metal stop cocks with steel cores and brass shells to prevent binding. In the bottom of the cylinder is located a ground joint which can easily be rotated from the outside without affecting the vacuum. To this joint on the inside of the cylinder is fastened a number of attachments for turntables used in the production of films of uniform thickness over large areas, and for various other experimental purposes.

The vacuum system, which has functioned very satisfactorily, consists of a 4-in. all metal Distillation Products, Inc. [DPI] vertical diffusion pump operating with Butyl Sebacate "Special" oil, or Amoil, and a Cenco Hypervac-20 fore pump. No traps were used in the system, although there were indications at times that a trap to prevent back streaming of the oil in the diffusion pumps would have been advantageous.

As is usual in such evaporators, pirani and ion gauges are used for determining the degree of vacuum attained. Low-reflection films are usually deposited at a pressure of 10^{-3} mm of Hg or less. Other materials, for proper film formation, must be evaporated at pressures of 5×10^{-4} to 10^{-5} mm of Hg.

The cleaning of the glass to be coated is very important. A film deposited on improperly cleaned glass (if it forms at all) is likely to develop blisters and pinholes or to peel off. The standard cleaning procedure used during the greater portion of this research has involved washing the glass to be coated in a 20 per cent sodium hydroxide solution and then in 10 per cent nitric acid. The glass is scrubbed in each bath with diaper cloth. Washing is continued until a water film will cling to the whole surface, without drawing away at any point. If oils or grease are on the glass, they

must be removed with benzene and acetone. The glass is finally rinsed in tap water, sprayed with doubly distilled boiling water, and dried in a filtered hot air stream.

If pinholes are to be avoided, it is necessary that the surface of the glass to be coated be held upside down during the last stages of cleaning, and kept this way until the film has been deposited, as otherwise dust particles will settle on the surface.

Magnesium fluoride and cryolite are customarily evaporated in the tank from small mullite crucibles. A tungsten filament, placed as shown schematically in Figure 37, serves as source of heat for the evaporation.

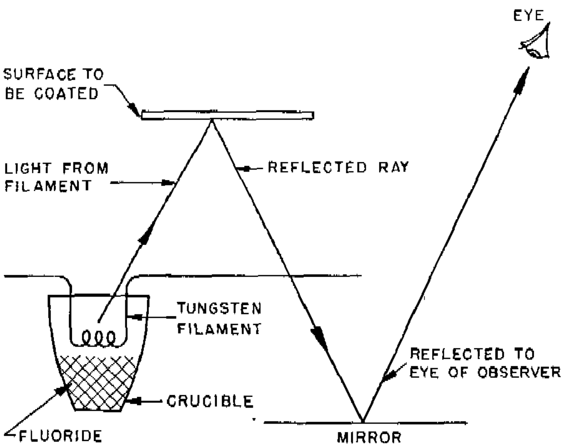


FIGURE 37. Schematic diagram of method of evaporating fluoride and of determining thickness of film deposited.

Figure 37 also shows the general method of determining the thickness of the film on the glass by viewing the color of the light reflected from the film-glass surface. Ordinarily, the film is deposited to a thickness such that light in the wavelength range[p] 5,300 A to 5,400 A (to which the eye is most sensitive) is very weakly reflected. Light of other wavelengths will be more strongly reflected. If white light is incident upon a low-reflection film of such thickness, the light reflected by the film will appear colored, for the green light (5,300 to 5,400 A) in the reflected beam will be very weak. To judge the thickness of the film, one thus examines the color of the light reflected from it. Light reflected from a film of the proper thickness for maximum transmission of light in the range 5,300 to 5,400 A appears purplish in color (or between red magenta and blue magenta as some writers say). A film for maximum transmission of 4,500 A appears amber or yellow by reflected light; a film for maximum transmission of 6,000 A appears blue by reflected light, and so forth.

[p] These figures represent a compromise between the wavelengths of maximum sensitivity of the eye for day and night vision.

9.5.2 High-Efficiency Partially Reflecting Films on Glass

In many optical instruments (reflex sight systems in particular) it is desirable to have a surface that will transmit part of the light incident upon it and reflect the rest. Frequently, thin "half-reflecting" films of silver or other metals have been used for this purpose, but these have several disadvantages. Silver tarnishes easily, and is inefficient. A silver film which reflects as much light as it transmits, will absorb 20 per cent of the incident light, reflecting only 40 per cent of the light, and transmitting 40 per cent. Silver is thus said to have an efficiency of 80 per cent. On the same basis aluminum has an efficiency of 70 per cent; most other metals have efficiencies which lie between 60 and 70 per cent. In the form of thin partially reflecting films, metals are therefore wasteful of light.

The disadvantages involved in the use of thin partially reflecting films of metal, can be overcome to a large extent through the use of transparent dielectrics which have almost no absorption coefficient and are therefore extremely efficient. In order to obtain a highly reflecting surface, it is desirable to evaporate onto the glass to be treated a dielectric film of refractive index higher than that of the glass, and of such thickness that the reflected beams A and B, as illustrated in Figure 36, are in phase and therefore interfere constructively. The proper thickness of the film in this case is one-quarter wavelength, as it was for the low-index material which was to prevent reflection. If the film illustrated in Figure 36 has a higher index than the glass, beam A will undergo a phase change of π upon reflection, but beam B will not undergo any. A phase change of π will be introduced, however, in B, due to the difference in optical path, if the film is one-quarter wavelength thick. Hence, under such conditions, the beams are in phase when B emerges from the film.[q]

[q] If a low-index film were deposited on the glass rather than a high-index film, the film thickness necessary to cause constructive interference would be one-half wavelength. It has, however, been found more satisfactory to employ high-index films in view of their greater durability, and in view of the possibility of using multilayer films (to be discussed presently) to increase the reflectivity to a high value.

For making such a high-reflection high-efficiency film, zinc sulfide with an index of refraction of 2.3 has been found satisfactory. A single layer of zinc sulfide deposited in a film one-quarter wavelength thick will reflect, on the average (the index of ZnS varies somewhat with the vacuum conditions), approximately 25 per cent of the incident white light. The transmitted light will appear very slightly tinged with color. This appearance of a colored transmitted beam is completely analogous to the appearance of a purple or magenta colored reflected beam in the case of low-reflection films. The high-reflection film, like the low-reflection film, is of the correct thickness for only one color of light, and in the case under discussion, the color is that to which the eye is most sensitive. The light transmitted by the high-reflecting film, like that reflected by the low-reflecting film, appears very slightly purplish or magenta in color. The light reflected by the high-reflection film, like that transmitted by the low-reflection film, is not colored to any noticeable degree.

High-reflecting high-efficiency quarter-wave films can also be made by fuming titanium dioxide onto glass. Such a film, which reflects 30 per cent or more of the incident light, is harder and far more permanent than a zinc sulfide film. Films of titanium dioxide deposited on properly cleaned glass will not show pinholes even if cleaned with Bon Ami (if the pressure applied during rubbing is not too great), and can easily withstand washing with water, dilute acid, acetone, or any other mild cleansing agent.

The most satisfactory method of fuming titanium dioxide is as follows: A 10-in. evaporating dish is half filled with titanium tetrachloride which is heated to a temperature of approximately 60 C. A jet of compressed air passing through a funnel 3 in. in diameter is played on the surface of the liquid. A cloud of dense white smoke arises from the dish, where the chemical reaction taking place is

$$TiCl_4 + 2H_2O \rightarrow TiO_2 + 4HCl.$$

The glass to be coated is heated to a temperature of 200 C and plunged into the cloud. The film will be deposited more uniformly if the glass is moved in and out of the cloud in a random fashion during the time of application of the film. Likewise, it has been found that a film deposited very quickly is more uniform than one deposited slowly.

The temperature of the glass is an important factor in determining the hardness and index of refraction of the film deposited. Films deposited on glass at room temperature are soft and foggy. The vapor pressures of the titanium tetrachloride and of the titanium dioxide and the temperature of the tetrachloride are also very important in determining the results obtained. Experience with the process will allow one to adjust the conditions so that the most satisfactory film will be formed.

The thickness of the film at any time during its formation can be judged from the reflections from the surface. When the film has the proper thickness it will reflect a bright white color. If it appears somewhat yellow, the film is too thick.

In applying the film, rubber gloves should be worn to protect the hands from acid fumes, and all work should be done under a hood with a strong air intake.

The percentage of light reflected by these high-efficiency films may be increased through the use of a multilayer film made up of alternating layers of high- and low-index materials. Two such multilayer films are shown schematically in Figures 38 and 39.

Figure 38 shows a film of high-index material overlayed with a film of low index. The reflected rays *B* and *C* undergo a phase change of π upon reflection; ray *A* undergoes no phase change upon reflection. If the high-index film is one-quarter wavelength thick, *A* and *B* will be in phase, and the light is strongly reflected; if the low-index film is one-half wavelength thick, *A*, *B*, and *C* are all in phase and the light is even more strongly reflected.

Figure 39 shows a film composed of three layers. A second high-index film has been added to the multiple film illustrated in Figure 38. In this new multiple film the beam *C* no longer experiences a phase change. If the low-index film is one-half wavelength thick as in the case previously discussed, *B* and *C* will be out of phase. If the low-index film is made one-quarter wavelength thick, rays *A*, *B*, *C*, and *D* will all be in phase and the light will be very strongly reflected.

A simple multilayer film of alternate quarter-wave layers of zinc sulfide and cryolite reflects an increasingly greater percentage of light as more layers are added. It also becomes more selective in its transmission and reflection as the layers are added. This, unfortunately, limits many of its applications. In Figure 40 are illustrated the transmission curves of multilayer films containing various numbers of zinc sul-

fide layers. The narrowing of the range of wavelengths transmitted as the number of layers increases is very noticeable.

Through use of the proper number and thicknesses of alternate layers of zinc sulfide and cryolite, it is possible to produce filters[r] of almost any desired transmission curve. In order

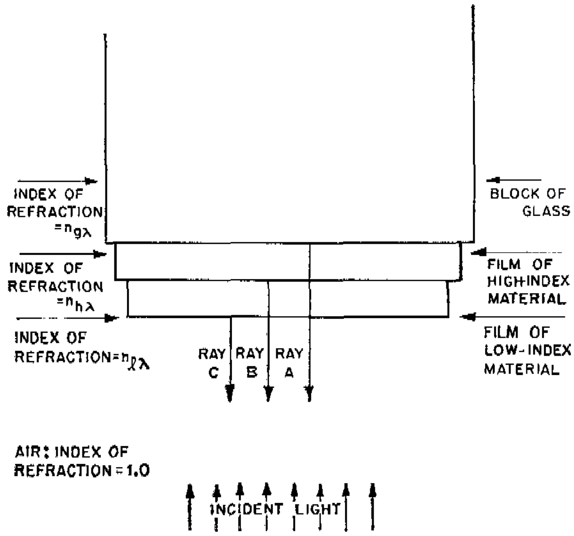


FIGURE 38. Rays of light reflected from two-layer film on glass.

to obtain a multilayer filter having a sharper wavelength cutoff than those exhibited by the films whose transmission curves are illustrated in Figure 40, one of several procedures may be followed: The thickness of either the cryolite or zinc sulfide may be changed, the layers may be changed to a higher order of interference,[s] or more layers may be used in the film.

A high-efficiency multilayer film can also be made up of alternate layers of titanium dioxide and cryolite. In Figure 41 are represented schematically some of the types of titanium dioxide-cryolite films that have been tested. Beside each filter will be found its observed and computed (multiple reflections were neglected) value of reflectivity for white light. Multilayer films made up with titanium dioxide are far more durable than those made with zinc sulfide. In the half-reflecting form, a titanium dioxide multilayer film is quite neutral, having only a slight brownish yellow tinge. Its efficiency is approximately 99 per cent.

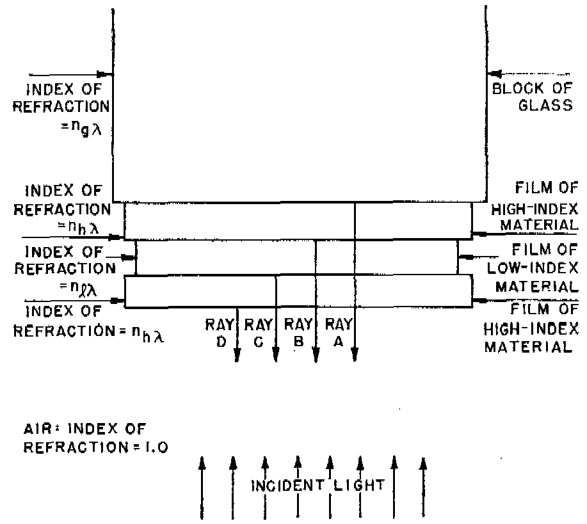


FIGURE 39. Rays of light reflected from three-layer film on glass.

9.5.3 Polarizing Beam Splitters

In some instruments it is desirable to have a beam splitter that reflects half the incident light and transmits the remainder, completely plane polarizing both the reflected and transmitted beams.

Normal white light incident upon and reflected from a piece of ordinary plane glass at the angle of polarization (the Brewsterian angle) is completely plane polarized. The transmitted light is not completely plane polarized, however, for although glass at the Brewsterian angle will reflect only the component of unpolarized light whose electric vector is perpendicular to the plane of incidence, its reflectivity for that component is only 15 per cent. The remainder of the light of that component is therefore transmitted, and is mixed with the other completely transmitted component whose electric vector is parallel to the plane of incidence. By means of a multilayer film, the reflectivity of the glass for the component whose electric

[r] Including neutral filters.

[s] If a cryolite layer three-quarters wavelength thick rather than one-quarter wavelength thick is deposited, the percentage of light reflected for that wavelength is not changed. The width of the reflection band will be greatly narrowed, however. This band will become still narrower if the film thickness is made five-quarters wavelength thick, and so on. These same effects are true for changing the thickness of the sulfide film to obtain higher order interference.

[redacted]

vector is perpendicular to the plane of incidence can be increased, and therefore the purity of the polarization of the reflected and transmitted beams can also be increased.

A successful polarizing beam splitter based upon this principle has been constructed by depositing alternate layers of zinc sulfide and cryolite on the hypotenuse faces of two 45-degree—90-degree prisms, and cementing them together as shown in Figure 42. In such a device there will be only one angle at which the beams are completely polarized, that angle depending upon the refractive index of the glass and the refractive indices of the materials of

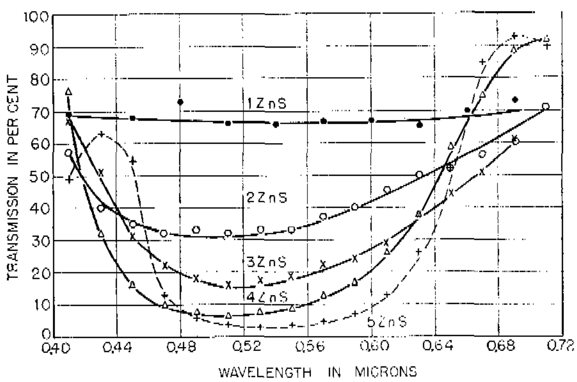


FIGURE 40. Transmission curves of multilayer (zinc sulfide-cryolite) films composed of various numbers of zinc sulfide layers.

which the multilayer film is composed. Over a total angle of approximately 10 degrees, however, the degree of polarization in both beams should be good. The degree of polarization of the transmitted beam will be determined by the number of layers in the film, and by the thicknesses of those layers.

If we stipulate that the angle ϕ in Figure 42 shall be 45 degrees, it can be shown that the conditions for polarization of the beams require that the following relationship must hold between the indices of refraction of the glass and the materials of the film layers:

$$n_g^2 = \frac{2n_l^2 \, n_h^2}{n_l^2 + n_h^2},$$

where n_g is the refractive index of the glass, n_l the refractive index of the low-index material, and n_h the refractive index of the high-index material, all at the same wavelength. Zinc sulfide, which has a refractive index of 2.3, has

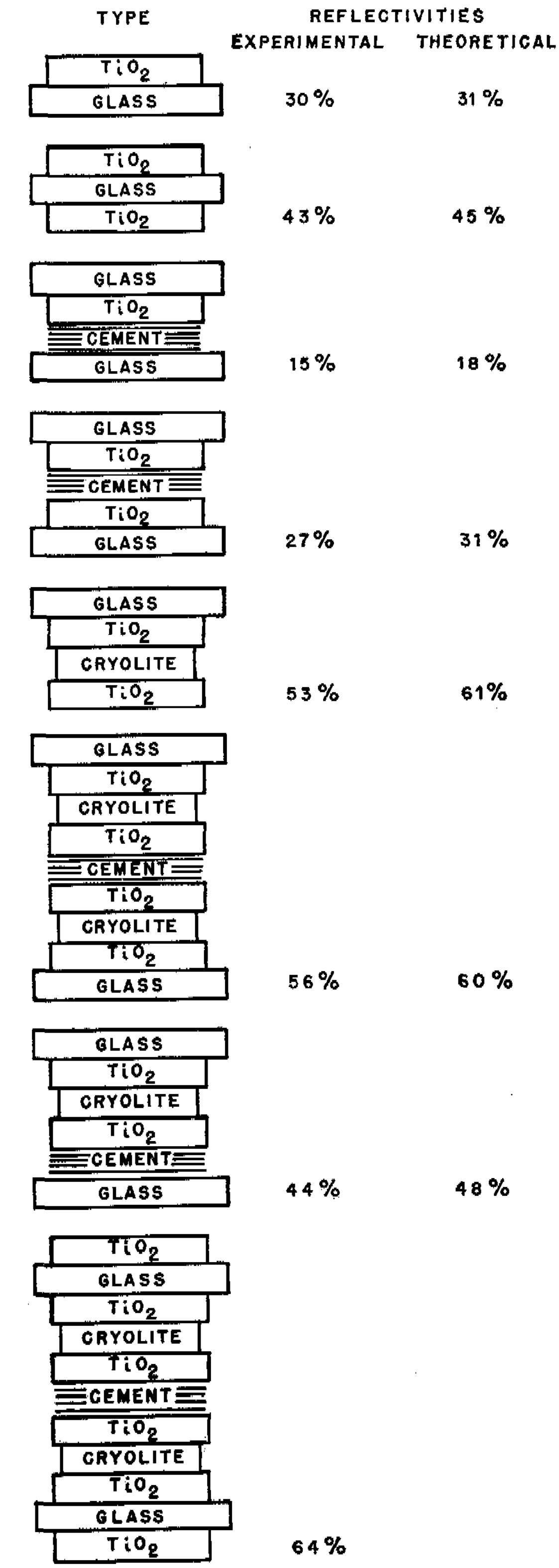


FIGURE 41. Types of multilayer titanium dioxide-cryolite films tested.

[redacted]

been found to be satisfactory for use as the high-index material. If we take n_h to be 2.3, and if we assume n_g to be 1.55, then n_l must be 1.25; if n_g is assumed to be 1.65, n_l must be 1.35.

The thicknesses of the films to be deposited may be computed from the readily derivable equations.

$$t_h = \frac{\lambda}{4} \cdot \frac{1}{n_h \cos \chi_1}; \quad t_l = \frac{\lambda}{4} \cdot \frac{1}{n_l \cos \chi_2};$$

$$\sin \chi_1 = \frac{n_g}{n_h} \sin \phi; \quad \sin \chi_2 = \frac{n_h}{n_l} \sin \chi_1.$$

The angle ϕ, as has already been pointed out, we take as 45 degrees.

Zinc sulfide has a high dispersion, $\nu = 17$. In order to compensate for this and to make certain that all wavelengths of light reach the interfaces of the high-index and low-index materials at approximately the critical angle for

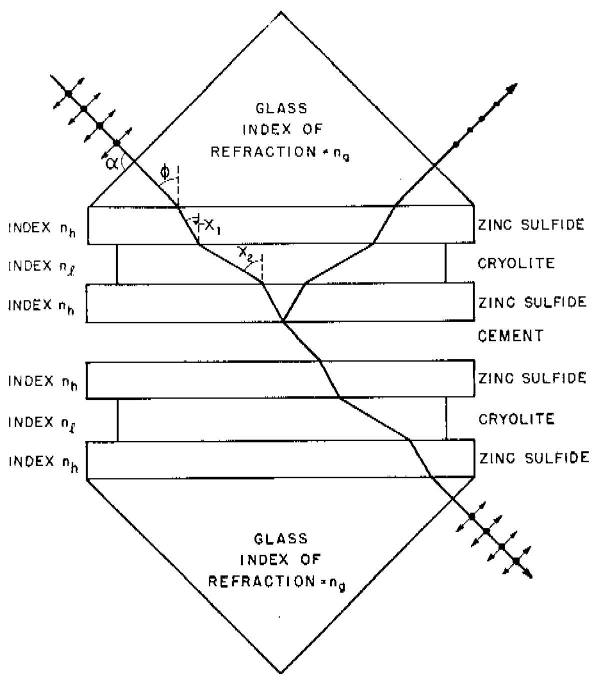


FIGURE 42. Schematic diagram of polarizing beam splitter.

polarization and reflection, glass of a particular dispersion must be used for the prisms. It may be shown that if all wavelengths do reach the interfaces at the critical angle, the following relationship must exist between the dispersion of the glass ν_g, the dispersion of the material of the high-index film ν_h, and the indices of refraction already introduced:

$$\nu_g = \frac{n_g(n_l^2 + n_h^2)\,\nu_h(n_g - 1)}{n_h(2n_l^2 - n_g^2)\,(n_h - n_l)}.$$

If $n_h = 2.3$, $\nu_h = 17$, and $n_l = 1.25$, we can predict that the glass most suitable for the beam splitter will have the optical constants $n = 1.55$ and $\nu = 48.5$. Two glasses exist which have approximately these constants. Extra light flint has the constants $n = 1.56$ and $\nu = 45.5$; light barium crown has the constants $n = 1.57$ and $\nu = 56.8$. The light barium crown would show a slight dispersion effect; the extra light flint would be very suitable for the polarizing beam splitter, since its constants match quite closely those determined from theory.

If a low-index material having an index of 1.35 rather than one having an index of 1.25 is combined with the zinc sulfide, glass having the constants $n = 1.65$ and $\nu = 46.5$ is required for the best results. These constants are matched most closely by those of extra dense flint glass for which $n = 1.65$ and $\nu = 33.8$. The difference between the dispersions of the theoretically best glass and the available extra dense flint is rather large; hence a dispersion effect is to be expected in a beam splitter made of this glass.

Beam splitters were made up on prisms of these glasses at the University of Rochester. The results obtained are summarized in Table 6 which gives the ratio of the intensity of the undesired component to the intensity of the desired component in both the transmitted and reflected beams at a 45-degree angle, and in three colors. As was anticipated, the polarizer made of the light barium crown glass is the most satisfactory.[t] The degree of purity of polarization[u] achieved in all three is, however, quite good.

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[t] Only three layers of zinc sulfide were put down on each prism for this polarizer; four were used with the other prisms.

[u] It can be shown that the reflected beam will never be completely polarized; a small percentage of the undesired component will always be found in that beam owing to the reflection taking place at the glass-zinc sulfide interface.

[redacted]

TABLE 6. Purity of polarized light reflected and transmitted by polarizing beam splitter.

Type of glass	Low-index material	Ratio undesired to desired component at 45 degrees Red	Green	Blue	
extra light flint ($n = 1.56$, $\nu = 45.5$)	cryolite ($n \sim 1.25$)	0.0035	0.0065	0.0103	Refl.
		0.0138	0.0031	0.0545	Trans.
light barium crown ($n = 1.57$, $\nu = 56.8$)	cryolite ($n \sim 1.25$)	0.002	0.002	0.002	Refl.
		0.02	0.015	0.02	Trans.
extra dense flint ($n = 1.65$, $\nu = 33.8$)	lithium fluoride ($n \sim 1.35$)	0.0033	0.0065	0.0035	Refl.
		0.014	0.013	0.0103	Trans.

9.5.4 Metallic Films

The properties of various metallic films deposited by the evaporization process have been studied during the course of this work.

ALUMINUM

Although the reflectivity of aluminum is less than that of silver for visible light, it does not tarnish so easily as silver, and is therefore frequently used for front surface mirrors. Evaporated in any vacuum better than 10^{-3} mm of Hg, aluminum will reflect 90 per cent of the visible light. This reflectivity falls off slightly in the near infrared and in the ultraviolet. By evaporating aluminum at different pressures the ultraviolet reflectivity can be greatly changed. A film evaporated under a pressure of 10^{-3} mm of Hg will reflect only 65 per cent of the incident light of wavelength 2,650 A. A film deposited at a pressure of 5×10^{-5} mm of Hg will reflect 90 per cent of the incident light of wavelength 2,650 A. Reflectivity curves for aluminum films deposited under different pressures are shown in Figure 43.

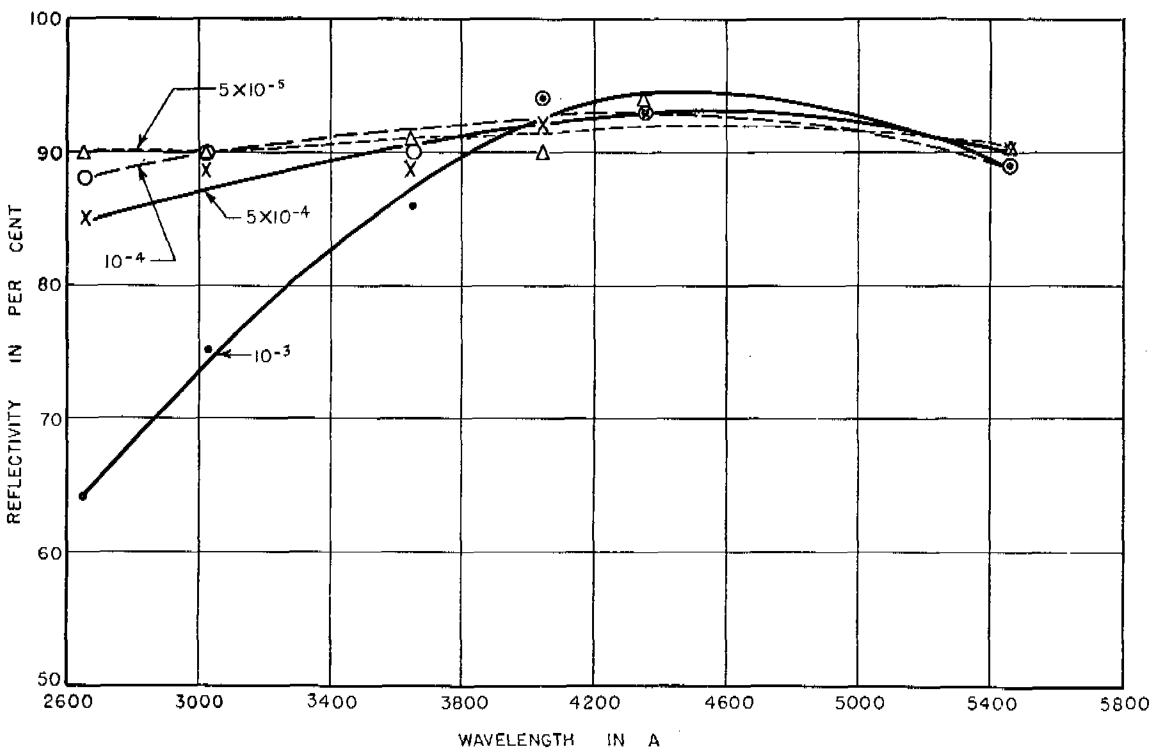


FIGURE 43. Reflectivity of aluminum films deposited at various evaporating pressures.

[redacted]

It was found that the frequent blistering of aluminum films subsequent to the evaporation could, in large part, be prevented by heating the glass to be coated to a temperature of 120 C during the evaporation of the aluminum. The best heating cycle for the particular size and shape of element being coated can readily be determined by experimentation. The glass must not be coated when at a temperature higher than 120 C, as mirrors formed at these higher temperatures have a bluish scattering cast. For best results the film should be deposited quickly and the glass surface to be coated should be at least 6 in. from the filament.

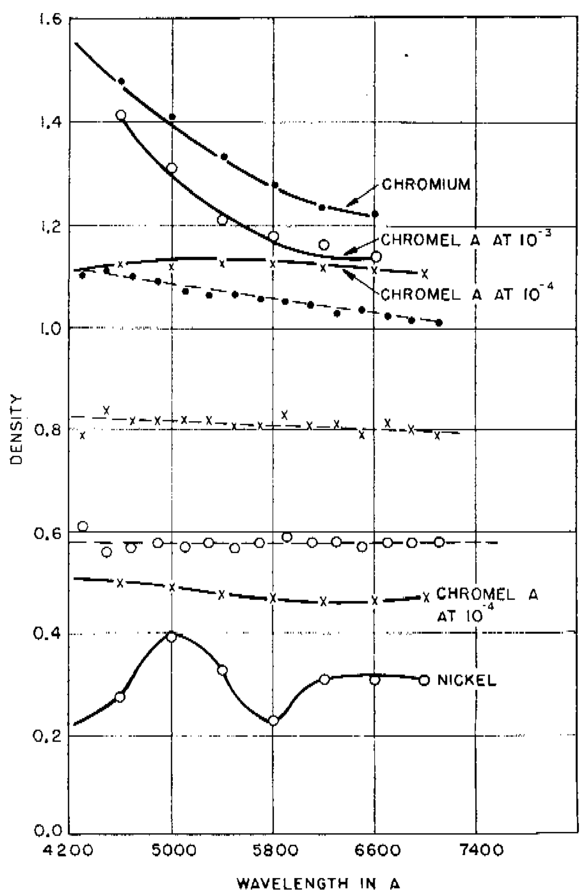


FIGURE 44. Transmission curves for various metals evaporated at various pressures.

Silver and Copper

Second surface mirrors can be coated very successfully by the evaporation process. A film of silver is deposited first, and then a thin coating of copper is evaporated over the silver to protect it from oxidation. These films are deposited in the same vacuum, the silver never being exposed to air until after the protective coat of copper has been deposited. As a final protection, the copper is coated with Nicholas black rubberized lacquer and baked for 3 hours at 70 C.

Blacks

It is often desirable to have a nonreflecting highly absorbing surface on which a pattern can be engraved. Zinc, tellurium, antimony, bismuth, gold, silver, copper, aluminum, and chromium all produce good sooty black surfaces if evaporated at a pressure of a few millimeters of Hg. The surface to be blackened must be placed quite close to the source of the metal if an opaque film is desired; the films are all very soft and do not withstand high temperature.

AgCl, precipitated out of $AgNO_3$ solution with HCl and then melted in air, evaporates to a black that is not sooty and reflects less light than glass. This film is hard and will withstand considerable heat, but cannot be coated over aluminum since a chemical reaction takes place which destroys both films.

Natural Density Filters

If Chromel A wire (80% nickel, 20% chromium) is evaporated from tungsten at a pressure of 10^{-3} mm Hg, a film of pure chromium will be deposited, as shown by the fact that the film has the same transmission curve as chromium and shows no chemical trace of nickel. If the pressure is reduced, however, to 10^{-4} mm of Hg or lower, a good deal of nickel is evaporated along with the chromium and the resulting film will show the same transmission for all parts of the visible spectrum. This neutrality continues throughout the ultraviolet to 2,500 A and to at least 1.3 μ in the infrared. (See Figure 44.) Like most neutral films made of a metal deposited on glass, the degree of neutrality attained with Chromel A is a function of the density of the filter. Films of Chromel A are quite hard and their reflectivity is rather high.

9.5.5 Conclusion

The many varied uses of thin films in the field of optics are only beginning to be realized, and the techniques involved in their production are far from being in a state of final perfection. Much research work remains to be done in this field of optics, many important problems remain to be solved, many even to be discovered.

9.5.6 Recommendations by NDRC

1. The search for new and more satisfactory materials for forming low-reflection and high-efficiency films by the evaporation method should be undertaken. While several searches for such new materials have been made, an extensive *systematic* one for new materials has never been made. In such a systematic study of the properties (both optical and mechanical) of the films tested, an attempt should be made to draw conclusions about groups or classes of compounds so that predictions of properties can be made.

2. A search for materials that might be used in the dipping or spinning process should be started. There is no obvious a priori reason to believe that a dipping method at least as good as—possibly even better than—the present evaporation process cannot be found. Even the acid etching method of forming low-reflection films cannot be ruled out as a completely undesirable process, and it, too, should have further attention.

3. The possibility of changing the reflectivities of metallic films by changing the conditions under which they are evaporated should be investigated. The results on aluminum discussed in this report are of considerable importance. A further study of the phenomenon not only for aluminum but also for other metals should be started at once.

4. The formation of protective coats of quartz or ceramic materials over films that are fragile or subject to tarnish should be re-examined. Some work on this subject has already been done, but many questions remain to be investigated. The study should include an examination of the whole problem of the evaporation of very refractory materials, including the effects of such materials on the heating filament. Data pertaining to these problems would be of great interest in many fields other than optics.

5. Sputtering as a method for forming films of materials not amenable to the evaporation technique should be investigated. Films of the same material formed by sputtering and evaporation may differ in their properties sufficiently to be of interest.

The problems that have been suggested here are all fundamental. Many more problems in the improvement and application of polarizing beam splitters, multilayer film filters, and other multiple films should be investigated. There are also many practical problems in technique which need further work. In particular might be mentioned the desirability of an objective, possibly wholly automatic, device for determining the thicknesses of the films, as they are deposited.

It seems likely that a number of research workers could very profitably be kept busy for some time in the investigation and application of thin films in the field of optics.

Chapter 10

OPTICAL SYSTEMS FOR TELESCOPES AND BINOCULARS

By *James G. Baker*[a]

UNDER CONTRACT OEMsr-160 the Institute of Optics at the University of Rochester developed a number of unique variants of low-power telescopes and binoculars. These devices resulted from an extensive program devoted to improved night vision.

Telescopes designed for use at low levels of illumination must have characteristics not usually found in systems for daytime use. The most important of these are large exit pupils and large real and apparent fields. The former makes it possible for the enlarged pupil of the dark-adapted eye to be filled with light transmitted by the instrument and also makes it easier to locate the exit pupil of the instrument with the eye. The wide real field provides a great advantage in searching for dimly illuminated objects and for silhouettes, and the associated wide apparent field reduces the impression that one's field of view is very much restricted by the telescope. The development of antioscillation mountings for telescopes has introduced a third important requirement on the telescope design, namely, that the instrument have large eye relief so that the eye may be placed at the exit pupil without any part of the head touching the antioscillation-mounted parts of the instrument.

10.1 WIDE-FIELD SYSTEMS AND SCHMIDT ERECTORS

In the design of wide-field telescopic systems of medium and high power, most of the difficulties arise in the design of the eyepiece. In most cases the residual aberrations of even the very best eyepiece design are larger than the residual aberrations of the objective, which is usually a cemented doublet. However, in low-power systems of wide field, the characteristics of the objective must also be considered. Moreover, it is possible by means of very complicated forms of objective to obtain improved flatness of field, but the possibilities depend markedly on choice of magnification.

The general principles of an eyepiece imply difficulty. The effective stop of the system is far removed from the elements, which in turn means that both distortion and astigmatism can reach large proportions. Much of the positive power of an eyepiece must be placed at low ray-height, which means that a large Petzval sum is inevitable. Because of the need for field-lens action of the eyepiece as a whole, the inclusion of negative power near the focal surface for the purpose of flattening the field becomes impractical. Finally, the negative type of eyepiece with a real focal plane between the lenses must be ruled out because of the small eye relief afforded.

It is necessary to design compound lenses that control the course of highly refracted rays in the outer part of the field. The requirements of color correction in a limited space and flattening the field at the expense of astigmatism mean that dense flint lenses must often be used, together with highly curved surfaces.

Fortunately, the aperture of any pencil is limited by the iris of the eye. Usually, spherical aberration and even coma of the eyepiece can be neglected, except where the amounts left in the design are excessive or where very large exit pupils are demanded. The most important aberrations of an eyepiece are therefore astigmatism, curvature of field, and lateral color. Very often, distortion must also be kept within specified limits.

An Eyepiece with Aspheric Surface. Two wide-angle eyepieces were designed under Contract OEMsr-160.[1] The first employs one aspheric surface and its characteristics are shown in Table 1.

Figure 1 shows a cross section of this design. The second surface from the left is parabolic, rather than spherical, and aids in the correction of the 80-degree total field.

[a] Harvard College Observatory.

The eyepiece unfortunately retains a large amount of lateral color, due to the impossibility of having the negative flint lens closer to the

TABLE 1. Characteristics of wide-angle eyepiece.

Focal length	25 mm
Exit pupil	7 mm (governed by eye at night)
Apparent field	80 degrees total
Eyepoint distance	22.7 mm

eye. The extreme wide angle, as used with a 6× objective combination, required a special design for the objective. The wide angle of the system also enlarged the erecting prism, which in turn required that the objective be of the inverted telephoto design, consisting of two separated doublets.

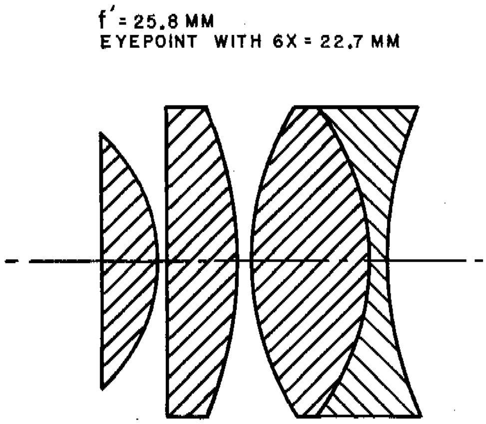


FIGURE 1. Aspheric eyepiece.

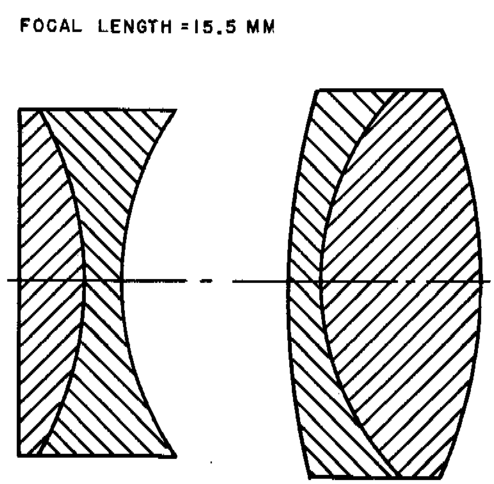


FIGURE 2. Objective A_3 for use with aspheric eyepiece.

Figure 2 shows the special objective for the 6× system. The combination of this objective

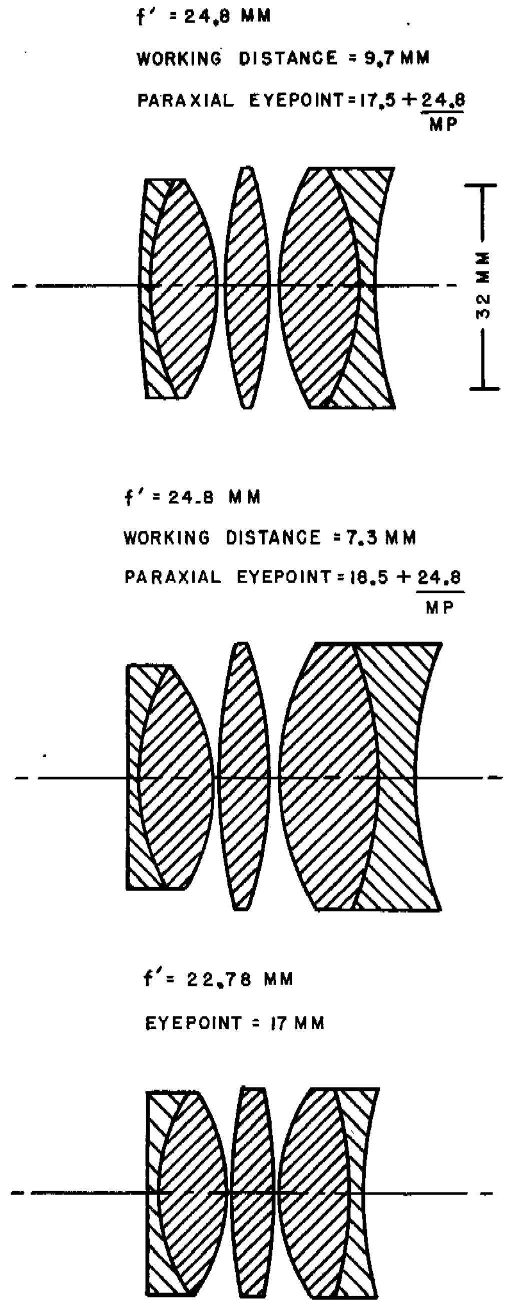


FIGURE 3. Types II-b, 37b, and 41 eyepieces.

with an erecting Porro system and the aspheric eyepiece yielded a real field of 14.28 total angle at 6×. The large apparent field of the eyepiece gives the observer the impression of actually

[redacted]

being nearer the object, with unobstructed vision.

Eyepieces II-b, 37b, and 41. An early eyepiece design developed under the contract was a modified Bausch and Lomb Erfle eyepiece, scaled to 25 mm equivalent focal length. The preliminary form was modified only slightly and is called II-b. Eyepieces 37b and 41 differ in eyepoint and compactness. Both are considered superior to II-b. Only spherical surfaces are employed.

Figure 3 shows the cross sections of the eyepieces. The general Erfle design is favorable for the elimination of both lateral and longitudinal color, although only the first is serious.

Compounded Systems. These three types of eyepiece have been combined with different prism and objective combinations to form 10×, 7×, 6×, and 3× telescopes. The optical characteristics are summarized in Table 2, and the various cross sections are reproduced in Figures 4, 5, 6, and 7.

Testing of the several completed instruments was carried out at the University of Rochester. Optical bench measures were similar to those for standard lenses, except that a real stop of 8 mm aperture was placed at the eyepoint. Data gathered in these tests were of great use in further designing.

In visual testing, an effort was made to carry out observations as objectively as possible.[1a] A chart was made up containing several sets of forty numbers arranged in various orders. Each set had four of each number from one to ten, in order to provide the same number of difficult numbers in each complete set of forty. The observer read off the numbers of successively smaller size until he began to make misses. The image size of the letters was recorded, and the angle subtended by the diagonal computed. Figure 8 shows a comparison of results with the NDRC 7x50 and Zeiss binoculars.

Flight tests of the 6x42 and II-b system at night indicated the great advantage of this type of wide-angle night glass for submarine detection.[2] The Navy soon took steps to procure more than one thousand units for night use. An added feature of tests made both with the 6x42 and 10x50 was the use of antioscillation mountings for aircraft work.

Figure 9 shows two views of the 3× telescope developed in connection with the *flightsight* (a reflex gunsight with radar indication, normally of unit power). The objective is a Cooke triplet, mounted between a forward Porro prism in parallel light, and a pair of mirrors between the elements serving as the second Porro. Such an arrangement permits the saving of weight, but even more important, allows for control of maximum illumination over the large real field of 23 degrees.

TABLE 2. Optical characteristics of University of Rochester telescopes.

a. 10x50 telescope*			
eyepiece	37b	f'	17.2 mm
objective	doublet	f'	172 mm
exit pupil	5 mm		
real field	7 degrees		
product of field by magnification	70		
eye distance	14.6 mm		
b. 7x50 telescope			
eyepiece	II-b or 37b	f'	24.8 mm
objective	doublet	f'	172.2 mm
exit pupil	7.1 mm		
real field	9.8 degrees		
product of field by magnification	70		
eye distance	17.6 mm with II-b 18.9 mm with 37b		
c. 6x42 telescope			
eyepiece	II-b or 37b	f'	24.8 mm
objective	doublet		
exit pupil	7 mm		
real field	11.6 degrees		
product of field by magnification	70		
eye distance	18.4 mm with II-b 19.66 mm with 37b		
d. 3× telescope			
eyepiece	37b	f'	24.8 mm
objective	Cooke triplet		
exit pupil	7 mm		
real field	23 degrees		
product of field by magnification	69		
eye distance	24 mm (approx.)		

* Has not been constructed.

Notes: Types a, b, and c make use of Porro Type 1 prism erectors. In d the real field is so large that the simple doublet objective is inadequate. The objective is a Cooke triplet, using three separated simple elements. This lens was designed with mirrors between objective and eyepiece to avoid the use of a heavy high-index prism needed for control of marginal rays (see Figure 7).

Also developed for auxiliary use with the flightsight is the system shown in Figure 10. The light first strikes a penta-prism, then a Cooke triplet objective, and then a roof prism. The system provides for a large real field of 23 degrees with a considerable offset between the optical axes of objective and eyepiece. In

both 3× instruments, lateral color is small and field curvature moderate.

One of the most striking optical systems developed under Contract OEMsr-160 is a monocular telescope making use of a perfected Schmidt prism erector. In the past the principal objection to use of a Schmidt erector, Figure 11, has been the presence of serious ghosts caused by the arrangement of the diagonal faces of the prisms. This great disadvantage has been overcome by coating the surfaces of the prisms with nonreflecting films. Further modification of the Schmidt prism erector permitted a shortening of the light path in glass and made it possible to incorporate the prism in a wide-angle monocular.

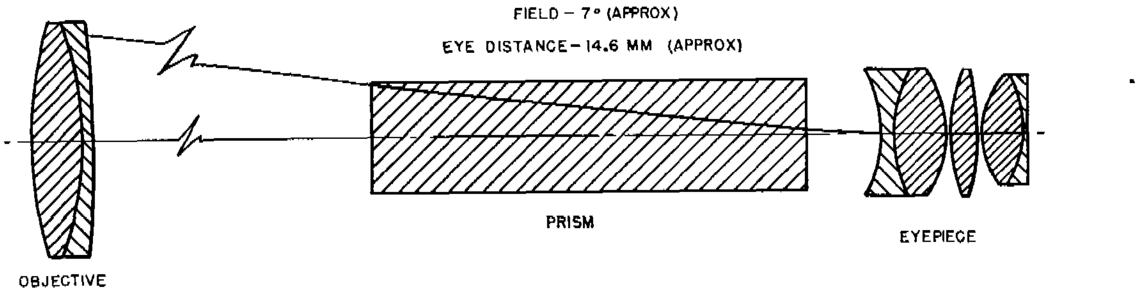


FIGURE 4. Optical system of 10x50 binocular.

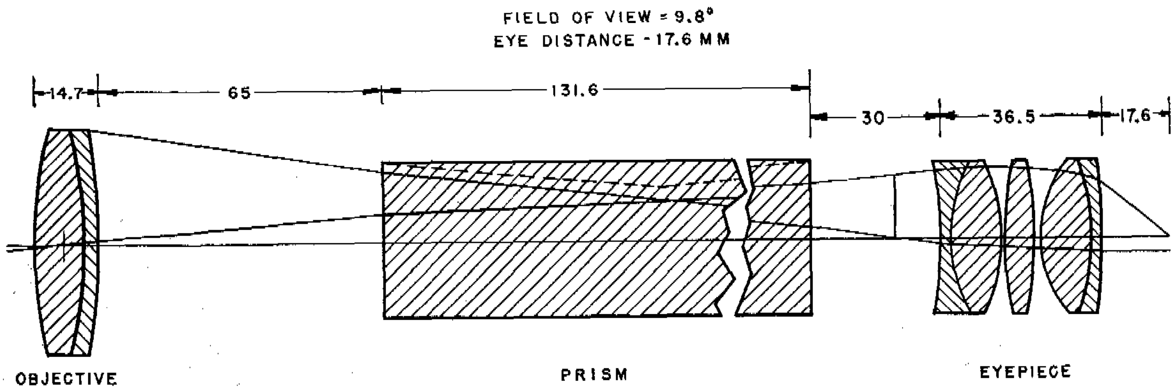


FIGURE 5. Optical system of 7x50 binocular.

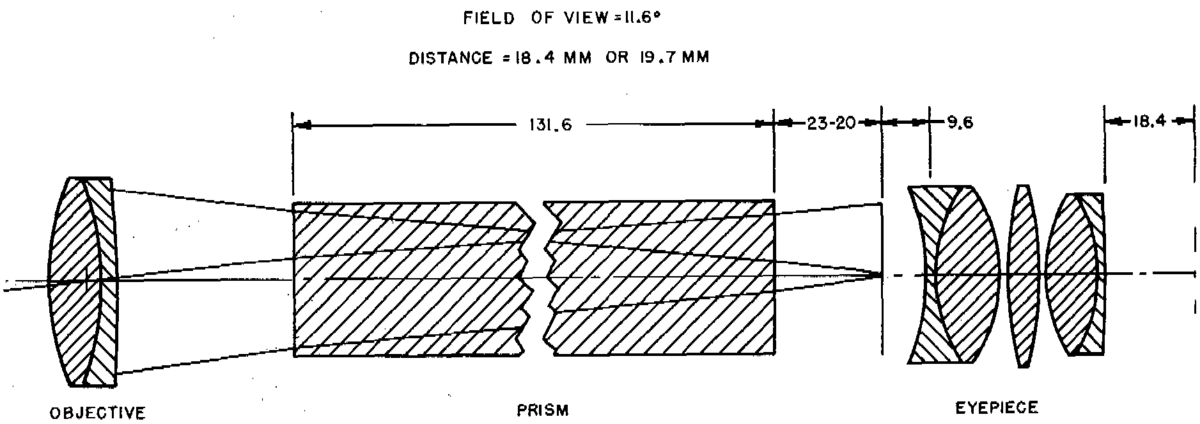


FIGURE 6. Optical system of 6x42 binocular.

[redacted]

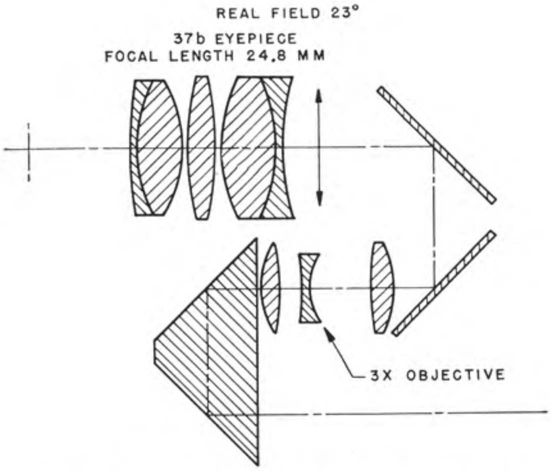


FIGURE 7. Optical system of 3× monocular.

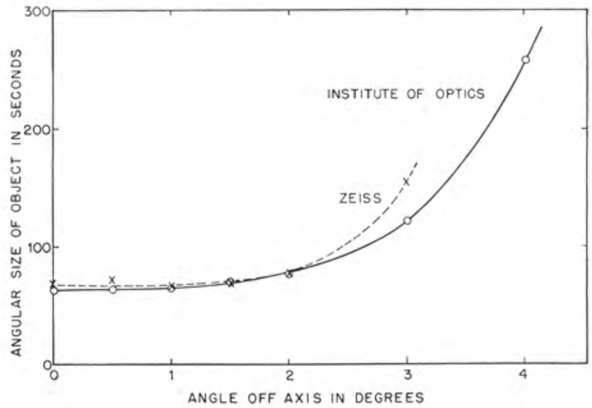


FIGURE 8. Resolving power of 7x50 and Zeiss binoculars.

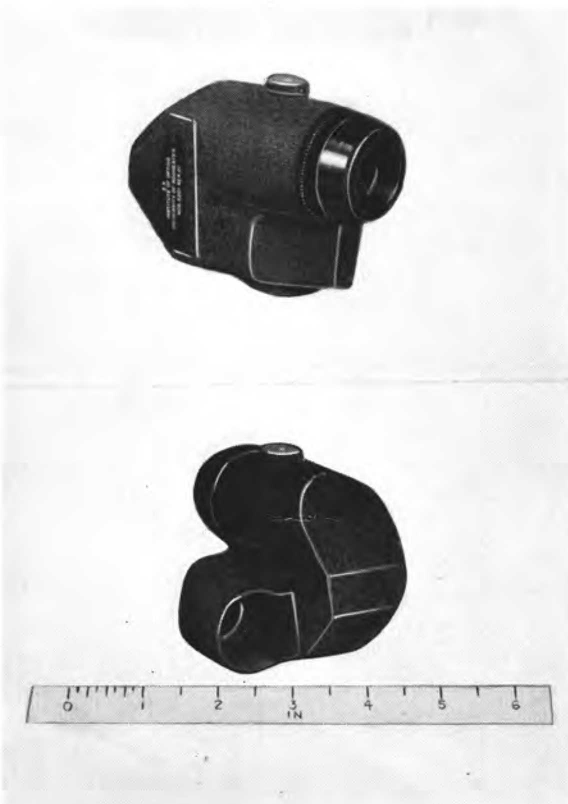


FIGURE 9. 3× telescope for flightsight.

FIGURE 10. 3× offset telescope for flightsight.

[redacted]

Figure 12 shows two views of this very compact type of wide-angle monocular. A service prototype was constructed, making use of the II-b eyepiece and 42 mm aperture doublet, resulting in a 6x42 system with 11.7-degree real field. A 3× objective consisting of two separated doublets is interchangeable with the 6× objective in cell, and parfocalized. The latter combination gives a real field of 23 degrees with exceptionally fine correction.

The II-c 10× glass, used in the night flight tests along with the 6x42, employed the complete optical system of the Zeiss Dekar. This instrument was later fitted with a new eyepiece of the 37b form, scaled to 19 mm focal length.

Substantial production of the 6x42 Porro-type instrument in antioscillation mount was undertaken by the Air Forces. The production of the 7x50 wide-angle binocular for general use was undertaken by the Navy Bureau of Aeronautics, although partially redesigned for production by the Bausch and Lomb Optical Company.

The 6x42 Monocular. This system is an advanced form of the 6x42 telescope already described. The chief alteration is the substitution of a Schmidt erector for a Porro-type prism, accompanied by minor changes in the form of objective. The objective was designed to correct for the spherical and chromatic aberrations of

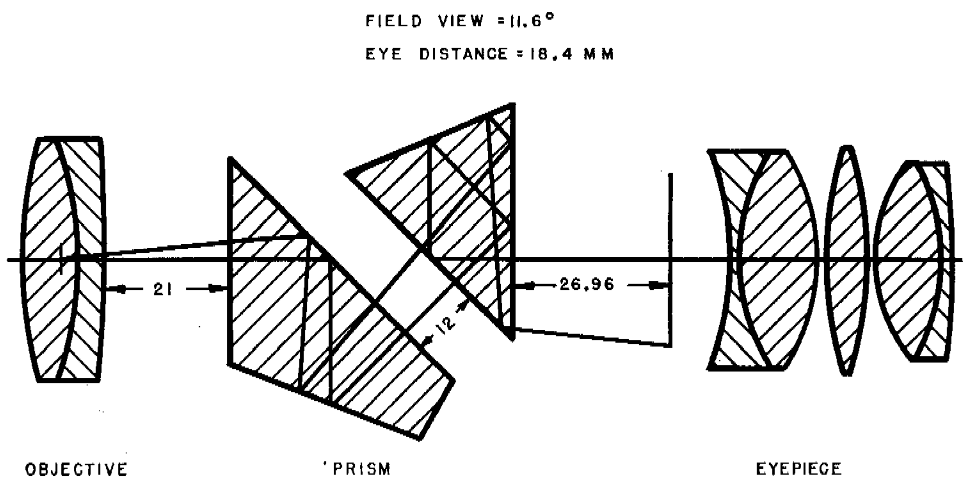


FIGURE 11. Optical system of 6x42 binocular telescope with Schmidt erecting system.

The modified Dekar has very good performance but is not quite equal to the performance obtained with the 10x50 design. The 10x50 has 50 per cent greater eye relief and an optical performance markedly superior to that of the standard Zeiss Dekar.

During the last two years of the war other types of instruments were developed.[3] Among these were 3×, 6×, and 7× telescopes with unusually wide fields. In the case of the 7× the product of field in degrees by the magnification has been made approximately 85 by the use of one aspheric surface in the eyepiece. The aspheric surface was produced by a molding process which has been much refined by the Institute of Optics and used in quantity production of other instruments.

the prisms and eyepiece. This monocular has a real field of 11.6 degrees, an eye relief of 19.66 mm, and an exit pupil of 7 mm. An Erfle-type eyepiece identical with that of the older instrument was used.

The optical system is as well corrected as possible, short of more elaborate design. Spherical aberration is imperceptible. Axial color has been reduced to secondary spectrum level which cannot be eliminated with available glasses. Coma of the system is completely corrected by the objective. Lateral color from the eyepiece and prisms cannot be eliminated entirely by the objective, but the residual is not objectionable. The tangential curvature is eliminated for the system, but there exists a large sagittal curvature owing to the succession of positive

[redacted]

powers. Eighty per cent of the field curvature is due to the eyepiece. Astigmatism is the most objectionable error remaining in the system.

The 3x21 Monocular. This monocular was similar to the 6x42, except that a new objective was provided, along with a change of glass type from DF-3 to LF-2 for the Schmidt prisms. Although an elaborate form of objective might have been used for the purpose of flattening the overall field, the particular application did not

FIGURE 12. 6x42 monocular telescope.

require the extra improvement. Consequently, the system was fitted with a simple cemented doublet, and was found to be adequate.

The 3x21 monocular was thereafter elaborated to include a 5-element objective with overcorrected Petzval curvature. It was found possible to design such an objective to eliminate the large errors of the eyepiece, and therefore to produce a system nearly fully corrected for flat field free from astigmatism. The report[3] states that at the edge of the field the astigmatism is less than 1 diopter. Coma in the objective was corrected to nearly zero. In addition, lateral color was adjusted until it became less than 2 min for the entire system. Tests showed that this instrument has a clear image field of constant quality throughout. The system has a real field of view of 23 degrees, an eye relief of 20 mm, and an exit pupil of 7 mm.

A 7x35 Monocular with Aspheric Eyepiece. This monocular was a 7× system with 5 mm exit pupil and 16 mm eye relief. The product of field by magnification for the instrument was 85.4 degrees. This apparent field was made possible only by means of using one aspheric surface in the eyepiece, namely, the first surface of the eye lens. It was found that the aspheric surface removed the distortion without materially affecting the astigmatic correction, and that the spherical aberration of the principal rays was greatly reduced, which in turn permits the eye position to remain fixed for oblique rays.

Correction of lateral color in this system required unusual extremes. The partial correction left over from the eyepiece was entirely eliminated in the objective by the use of two separated elements and a special chromatic plate. The objective corrected the system for spherical aberration and longitudinal color simultaneously. Figure 13 shows a cross section of the final design.

A 7x50 Monocular with Parabolic Surface in Eyepiece. A 7x50 monocular was required for use as a wide-field night glass. It was considered very important to obtain a long eye relief. In order to obtain this, an eyepiece of 25.8 mm focal length was designed, with the curved surface of the eye lens ground to a paraboloid. As in the system previously described, the objective is separated and the chromatic plate is used to correct for lateral color. A real field of view of 12.4 degrees is obtained along with an eye relief of 22 mm and an exit pupil of 7 mm. The optical system is shown in Figure 14.

The report[3] states that the performance of this system is excellent, although the transmitted image appears yellow due to a long light path through the dense flint Schmidt prisms. It is recommended that the 7x35 be used instead of this 7x50, and scaled up to comparable size if necessary.

A 3× Monocular. The 3x21 monocular described above was scaled down to have a real

field of 23 degrees and eye relief of 15.2 mm, along with an exit pupil of 5.4 mm. It was intended that this monocular be as light as possible and strapped to an operator's head. It was planned to insert an aspheric eyepiece with a focal length of 16.24 mm, which would result in a 3.69× telescope with the same real field as the 3× telescope. The end of the contract prevented completion of this design.

justify either the large field of view or American reproduction. Instead, efforts were made to design a glass of higher quality with a 70-degree apparent field. These efforts were successful, and later crystallized in a production model.

Mechanical design features of the wide-angle 7x50 glass were adapted to mass production, and departed slightly from requirements for minimum weight. In the end the manufactured

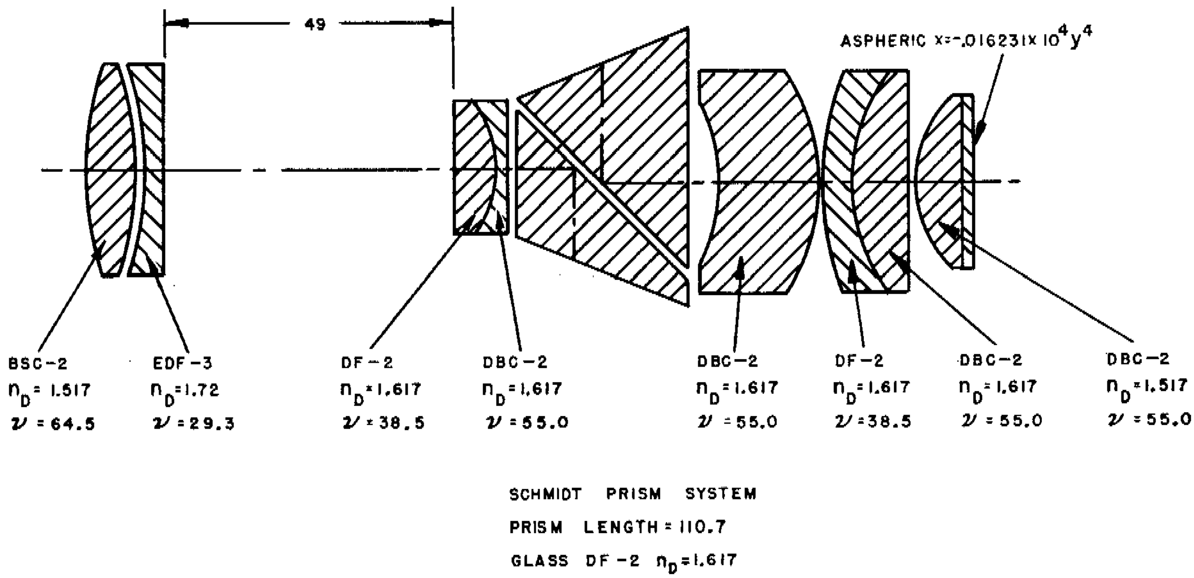


FIGURE 13. 7x35 monocular telescope.

10.2 7x50 BINOCULARS WITH 10-DEGREE FIELD

Under Contract OEMsr-579 the Bausch and Lomb Optical Company undertook requested variations in the design and construction of binocular systems.[4] With respect to optical design there were developed a 7x50 wide-field binocular with 10-degree field and a binocular with a 10-mm exit pupil, both intended for night use. A Bausch and Lomb eyepiece with large eye relief was fitted to several experimental binoculars. Several special eyepieces were designed and constructed for the use of Contract OEMsr-1229 at Brown University.

A study made of the Zeiss 8x40 binocular, rated for an apparent field of 90 degrees but which proved to have only 83 degrees, showed that the mediocre definition obtained did not glass weighed 68 ounces, compared to 49 ounces for the standard 7-degree glass, and 36 ounces for the fragile Zeiss 8x40.

The Zeiss tapered Porro prisms caused vignetting of rather serious proportions far off axis. Bausch and Lomb reduced this vignetting by returning once more to untapered prisms. The 7x50 glass of the Institute of Optics suffered partially by making use of the tapered Zeiss prisms.

A considerable amount of time was spent at Bausch and Lomb on computations of aspheric eyepieces. It is reported that no important improvement in definition could be obtained to justify the complication, although it proved possible to obtain better transmission far off axis.

A 10x50 Binocular with 7-Degree Field. Two samples of a Bausch and Lomb binocular meet-

ing the above specifications were delivered to NDRC for the Bureau of Aeronautics. The change consisted primarily of substitution of higher power eyepieces.

A 7x50 Binocular with Reduced Diameter at Eye End. Two samples of a binocular meeting these specifications were made up and delivered to NDRC in February 1944. These binoculars differed from the standard 7x50 only in the respect that the metal rims of the eyepieces were cut back to allow as much eye and nose room as possible. To facilitate such work, fixed focus eyepieces were adopted.

A 7x50 Binocular with Increased Eye Distance. Newly designed Bausch and Lomb eyepieces with large eye relief were fitted to two otherwise standard 7x50 binoculars. No details of the eyepieces are available since they are not NDRC designs. Two binoculars so equipped were shipped in April 1944, and two more in July 1944.

A Binocular with 10-mm Exit Pupil. Two sample binoculars were made up with 10-mm exit pupils for experimental work in night vision. These binoculars consisted of standard 7x50 systems equipped with scaled up Kellner eyepieces. The real field remained unchanged. These samples were shipped in January 1944 to NDRC. Later, four other samples were made up and delivered to NDRC in April 1944.

A Dummy Binocular. In accordance with experimental investigations on the influence of exit pupil diameter on the effectiveness of binoculars for night vision, Bausch and Lomb suggested that binoculars with no objectives or eyepieces could be used. Two dummy binoculars with the same size and field as the standard 7x50 were supplied in February 1944. The field inversion caused by the Porro prisms alone was removed by substitution of rhomboid prisms in the binocular bodies. The field of vision was partially restricted by these prisms. Nine pairs of exit-pupil diaphragms were also supplied, ranging in steps of 1 mm from 2 to 10 mm.

Additional Eyepieces. For use in the experimental investigations on binocular performance carried on at Brown University, Bausch and Lomb under Contract OEMsr-579 supplied

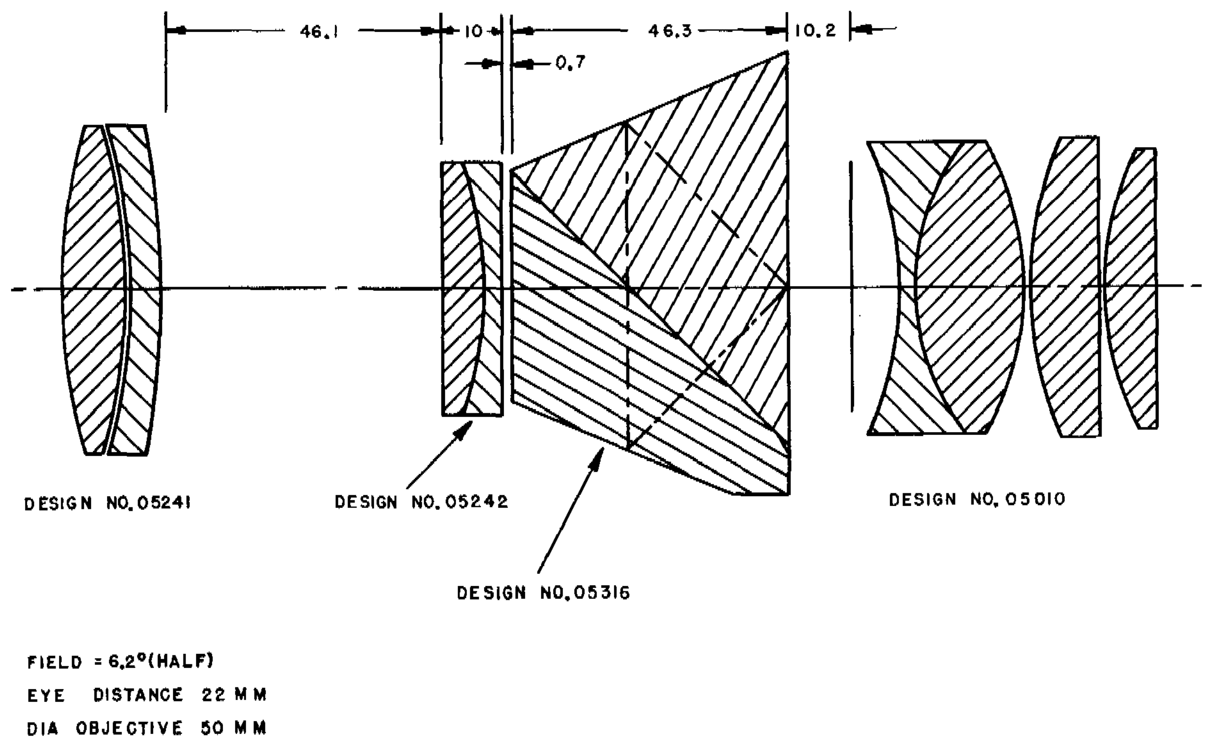


FIGURE 14. 7x50 monocular telescope.

[redacted]

three pairs of eyepieces of 14-mm focal length, and three pairs of eyepieces of 32-mm focal length, mounted to be interchangeable with the regular eyepieces of the Mark I, 7x50 binocular. These eyepieces provide powers of 14× and 6× respectively, when combined with the 7x50 objectives.

The eye distances and apparent fields of view for these eyepieces were as follows:

	eye distance	apparent field
14×	11.5 mm	30 degrees
6×	17.8 mm	41.5 degrees

The report[4] states that there are no special features of these eyepieces in either optical or mechanical design to justify further comment.

10.3 FOUR DESIGNS FOR TELESCOPE OBJECTIVES

Under Contract OEMsr-474 Harvard University was requested to make up several long-focus collimator lenses for use wherever needed by Army, Navy, or other NDRC projects.[5] Only one such collimator was made up, but four separate designs were submitted. There is nothing essentially new about these objective designs, but it is instructive to reproduce them here as carefully computed standard systems for visual use.

The best monochromatic correction has been taken for e light at 5,461 A, which is very close to the maximum spectral sensitivity of the eye. For all designs, F and C have been combined accurately for the 0.707 zone at $f/15$, and the rim ray at $f/15$ has been combined with the paraxial focus. Table 3 summarizes the optical constants of these objectives.

In every case the values listed in Table 3 are in units of the equivalent focal length. The objectives are listed in order of increasing quality. Objectives A and B are of the cemented type. Type B has less than half of the zonal aberration of lens A, and yet has shallower curves. The coma is very nearly of the same value but of opposite sign. Type C has the spherical aberration slightly reduced relative to type B, and is fully corrected for coma. It has broken contact at the inner surfaces and is called a Fraunhofer-type objective. Type D has only half the zonal aberration of Type C, and is equally well corrected for coma. The two elements of type D are air-spaced by such an amount that the internal radii are identical when the aberrations are eliminated. Further increase in air space would eliminate the zonal aberration altogether at $f/15$, but would lead to a noticeable increase in lateral color of the system.

Figure 15 shows a 6-in. lens of type D in a special cell. The completed lens yielded theoretical definition. The details of the cell design are shown clearly in Figure 15. It should be noted that the retainer rings do not bind against the elements but, by careful lapping in optical fashion, square against a shoulder just short of touching the lens surface. Provision is made for adjusting the air space for maximum performance, whereafter a spacer ring of suitable thickness is inserted for true centering of the elements.

TABLE 3. Optical constants of four simple objectives.

Surface	Radii	Separations	Indices e	Glass types
A.				
1.	1.0177	0.0070	1.51899	BSC-2
2.	—0.2877	0.0050	1.62115	DF-2
3.	—0.7336	0.9972		
B.				
1.	0.4645	0.0070	1.51899	BSC-2
2.	—0.4314	0.0050	1.62115	DF-2
3.	—5.2140	0.9922		
C.				
1.	0.6083	0.0070	1.51899	BSC-2
2.	—0.3544	0.0001		
3.	—0.3585	0.0050	1.62115	DF-2
4.	—1.4936	0.9941		
D.				
1.	0.5814	0.0069	1.51899	BSC-2
2.	—0.3585	0.0031		
3.	—0.3585	0.0050	1.62115	DF-2
4.	—1.6189	0.9868		

10.4 TANK TELESCOPES

Under Contract OEMsr-160 with the University of Rochester and Contract OEMsr-1078 with the Yerkes Observatory, the design and construction of several tank telescopes were accomplished. In 1943 the Frankford Arsenal was much interested in procuring an improved

[redacted]

tank telescope to match the acknowledgedly superior performance of the corresponding German and English equipment. A start had already been made at the Arsenal itself toward incorporation of a Cooke triplet objective instead of the conventional doublet. The resulting performance, however, still was below requirements.

10.4.1 Rochester Modifications

The tank telescope in production at Frankford Arsenal was examined at the University of Rochester and found to have the following specifications.[6] The apparent field of the eyepiece was 67 degrees, the exit pupil 7 mm, the overall length 28 in., and the maximum lens diameter 1.5 in. The optical system gave 3× and employed lens erection.

The time allotted for change in design was so short that it became necessary to make the quickest possible improvements[2a] rather than to redesign the system. Moreover, the production of the optical parts had already been initiated, which made it desirable to conserve the existing design as far as possible.

The chief aberrations of the existing 3× (T-76) tank telescope were found to be spherical aberration and color, both greatly in excess of tolerance. In addition, the eye relief was somewhat insufficient and the Petzval curvature of the system too large.

It proved possible to eliminate the color and most of the spherical aberration by means of a new erector system, consisting of new doublets and an achromatizing zero power plate inserted only for expediency. The resulting instrument was fully corrected for color and nearly corrected for spherical aberration. No improvement in the Petzval sum was possible by this interchange of doublet erectors, nor was it feasible to increase the eye distance.

The modified telescope was taken to the Frankford Arsenal for comparative tests. The results can be summarized as follows. The NDRC telescope in principle had transmission equal to that of the Bausch and Lomb sample, but was handicapped provisionally by uncoated surfaces and the presence of the chromatic correcting plate. The competing system of the Eastman Kodak Company was in general better corrected, but gave markedly reduced transmission and color to the image. The superior correction of this latter system was obtained at the expense of more complicated construction with more air-glass surfaces and unusual glass types.

The eye distances of all three telescopes were very nearly identical. The Eastman sample required that the eye be moved in order to see the entire field. The Eastman sample did not vignette as rapidly as the other two near the axis,

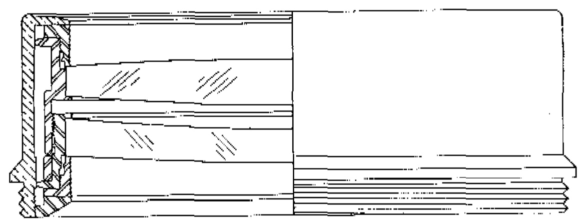


FIGURE 15. 6-in. aperture objective lens.

but vignetted more rapidly in the outer part of the field of view. The Eastman design showed considerable lateral color, but the Bausch and Lomb and NDRC models none. All the telescopes showed the same axial color, due mostly to secondary spectrum. The Eastman telescope showed marked spherical aberration compared to both the others.

Following these tests a redesign succeeded in eliminating the chromatic plate, and in replacing the original Arsenal doublets by new doublets with better spherical and chromatic corrections (see Figure 16). The resulting instrument yielded performance identical with that of the temporary model, and hence was deemed suitable for production purposes. The triplet objective and Erfle eyepiece were unaltered. In the meantime, modifications of the design at the Arsenal were believed to have accomplished a similar overall improvement. The final production therefore was in accordance with the Arsenal design.

The 5× Tank Telescope. The scaling up of the objective used in the 3× telescope was not advisable owing to excessive spherical aberration. Consequently, it was considered necessary to redesign not only the erecting system for a

5× system but the objective as well.[6a] Figure 17 shows a cross section of the 5× optical arrangement. The doublet erectors are identical and work at $f/5$. The Erfle eyepiece is identical with that used in the original T-44 and T-76 telescopes, even though it would have been desirable to enlarge the element diameters for reduction of vignetting had time limits permitted.

The optical performance is summed up in Table 4.

TABLE 4. Optical performance of the 5× telescope.

1. Spherical aberration:	half apert. (in.)	sph. aber. (in.)	tolerance (in.)
	0.69	0.022	0.01
	0.48	—0.014	0.015
	0.25	—0.01	0.02
2. Chromatic aberration:	half apert. (in.)	chr. aber. (in.)	tolerance (in.)
	0.69	0	0.0000098
3. Petzval sum: 0.764.			
4. Eye distance: 1.2 in.			
5. Oblique aberrations: Ray-tracing calculations show that the only important residual aberration off axis is astigmatism. When the eyepiece is focused for collimation of the axial bundle of rays, the sagittal rays at the edge of the field are out of focus by 2 diopters.			
6. Lateral color: Essentially zero over the entire field.			
7. Secondary spectrum: Customary residual.			

Conclusions. These telescopes do not represent the best that can be obtained in optical performance. Inevitably, some choice must be made between complication and practicality. More complicated systems could be designed with better image quality at the edges of the field. Even for the existing instrument, however, the image quality at the center of the field is designed to be as good as possible. Moreover, the shallowness of the curves of the instrument will ensure that production units will be of uniformly high quality.

In the case of the 3× telescope a slight improvement in quality at the edges of the field would have resulted if the objective of the T-76 had been altered. Inasmuch as the objectives were already in production, it seemed wiser to make use of the existing design.

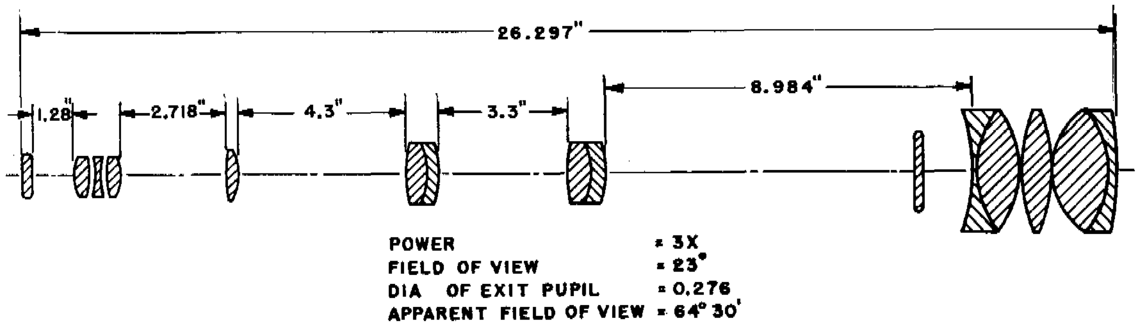


FIGURE 16. 3× tank telescope with a 23-degree field.

10.4.2 Yerkes Tank Telescope

The 3× tank telescope problem was considered so urgent that the Yerkes Optical Bureau under Contract OEMsr-1078 was also called on for an improved design.[7] The general restrictions were identical with those imposed on the Rochester modification, although the Yerkes program called for a complete redesign from the very beginning. The aberrations already found and described above in connection with the Arsenal design were evaluated at Yerkes and either eliminated or improved in the redesign.

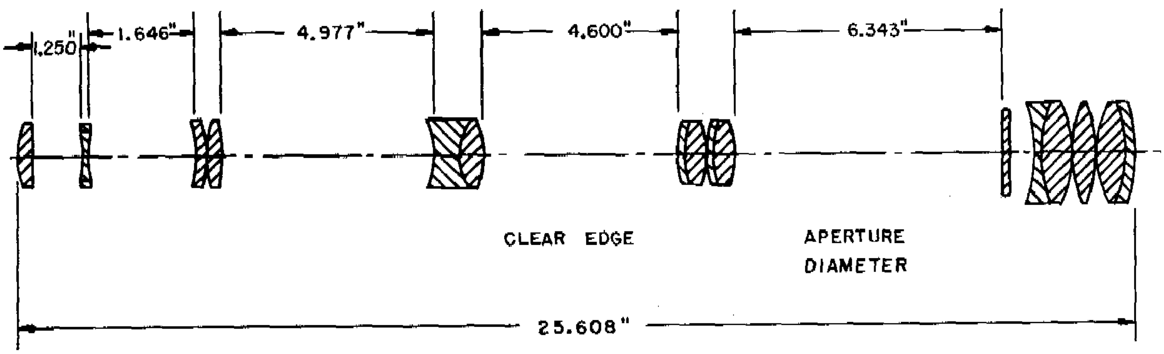
The requirements met by the Yerkes design included a 21.5-degree real field, a 7.8-mm exit pupil, and 2-in. diameter lens elements. The difficulties outlined by Yerkes to be overcome involved removing both the spherical aberration and the chromatic difference of spherical aberration from objective and erector system, the reduction of the Petzval sum to a minimum consistent with other details of performance, and the artificial flattening of the apparent field by introduction of a suitable amount of negative astigmatism.

[redacted]

The final lens design is shown in Figure 18. The objective is a widely separated Cooke triplet at $f/5$ for the axial bundle. The entrance pupil lies in the middle of the objective. The focal point lies 0.3 in. in front of a collective lens which tends to reduce the angular aperture of the bundle. The principal ray is bent so that it strikes almost centrally on the erecting system.

The erecting system consists of two separated doublets, each with a negative lens in front, and working at $f/3.5$. Between the erectors the light is parallel. The reticle is flat, and is viewed by an eyepiece similar to an Erfle design.

The aberrations in each component of the system are uncorrected in order to provide a greater degree of freedom in the overall design. The spherical aberration is almost completely corrected at the reticle. The astigmatism is greatly overcorrected at the reticle in order to compensate for negative astigmatism in the eyepiece.



POWER = 5X
FIELD OF VIEW = 13°
DIA OF EXIT PUPIL = 0.276
EFL OF OBJECTIVE = 5.625
EFL OF EYEPIECE = 1.625

FIGURE 17. 5× tank telescope with a 13-degree field.

The spherical correction of the system is achieved by proper choice of separations and powers. The objective is corrected within the Rayleigh limit. The correction of the erecting systems is aided materially by means of the slight convergent effect of the collective lens which lies away from the focal plane of the objective. In both of the erectors the negative flint lens is placed in front with an appreciable air space. The optical system as a whole is extremely well corrected.

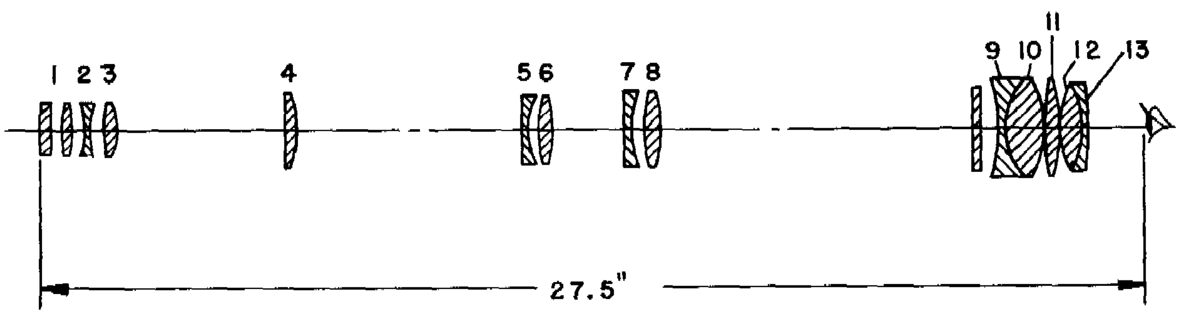


FIGURE 18. Yerkes 3× tank telescope.

It proved possible by choice of these various separated elements to reduce the Petzval sum

of the system appreciably as compared to a system of all positive lens elements. The final system gives a much flatter field than the T-93 Arsenal design.

Investigations Leading to the Final Design. Much effort was put on reduction of the Petzval sum. Toward this end, triplet objectives with still greater air spaces were attempted. However, the longer triplets were afflicted with higher order coma and had to be discarded. It usually proved possible to control the higher order spherical aberration.

Similar attempts were made to construct the collective lens of three separated elements. These calculations showed that such a collective lens could not be used because of the large refractions involved. Consequently, the collective lens, which constitutes a chief source of the large Petzval sum, was made of a single high-index element.

Many calculations were expended on improving the erecting system. A fully symmetrical system of four separated elements was tried in hopes of procuring extremely good correction at unit magnification. Unfortunately, when the erecting system was almost exactly corrected for zonal spherical aberration, there remained positive astigmatism of considerable magnitude. Although use of an aspheric surface on the eyepiece might help, this system was abandoned.

The erecting system chosen, as shown in Figure 18, provides a control on both astigmatism and errors in the aperture. Indeed, the erecting system was considered to include the collective lens and was corrected for overall performance. Although the total field curvature is already large at the reticle, the markings are only in the central one-fifth of the field. Since the spherical aberration of the system is well corrected at the reticle, the system does not have an axial parallactic shift anywhere in the exit pupil.

The eyepiece design was based on the Erfle type but was the subject of a separate investigation. For the sake of convenience and effectiveness, the calculations were based on the equivalence of the three eyepiece elements to two thin air-lenses of positive power. By changing the shape factors of the two air elements, it proved possible to introduce varying degrees of astigmatism into the eyepiece.

It is stated in the report[7] that if an aspheric surface could be used in the eyepiece as a source of large negative astigmatism, it would be possible to compensate the excess positive astigmatism that constituted the chief fault of the 4-element symmetrical erector. Moreover, if this aspheric surface could have been used, the overall performance with respect to coma and the chromatic variation of the aberrations might have been considerably improved.

The paraxial eye distance was set at 1.5 in., but at large field angles the spherical aberration of the pupil reduced this value to 1 in. The lateral color, common to most Erfle eyepieces, is large at half field and becomes small or of opposite sign at full field. The primary cause is chromatic difference of distortion. It is probable that some secondary spectrum in the lateral color may be present also.

During the design work there was some uncertainty as to the amount of anastigmatic flattening of field that could be introduced. To determine the answer, two eyepieces were constructed having different amounts of negative astigmatism. The first of these, T 14.57, had the larger negative astigmatism and required less eye accommodation to reach the surface of least confusion. The second, T 14.64, proved to give better definition at large field angles without exhausting the ability of the eye to accommodate to the field curvature. Indeed, still another eyepiece, T 14.65, with even less astigmatism, was made up and found to be satisfactory. The usual practice of flattening the tangential focal surface therefore led to unnecessarily large negative astigmatism.

The test models were built with oversize lenses. It was possible to obtain an exit pupil of 7.8 mm with slight vignetting nearly to the edge of a 23-degree true field. In a production model with heavier cells and smaller lenses in the collective and second erector, it would still be possible to obtain an exit pupil of more than 7 mm with a true field of 21 degrees. The limitation on the size of the axial pupil is set by the variation of spherical aberration with color, which is already detectable at the edge of the 7.8-mm pupil. The axial performance is ex-

cellent with the reticle sharply defined. The resolving power at full field is enough to detect a separation of 0.6 mils in object space, contrasted to an axial resolving power of 0.07 mils.

Table 5 gives the optical constants of the system. All dimensions are in inches, and all glasses standard Bausch and Lomb types.

Table 6 contains a comparison of performance data for T-14.64 and the T-93 tank telescopes. Complete data are tabulated in the original report.[7]

the field. Owing to the use of lighter glasses and one less element, however, it is likely that the total transmission of the T-93 design is slightly better than that of the NDRC design.

10.4.3 The Bifocal Bipower Telescope

The tank gunner is confronted with the dual problem of finding his target and obtaining

TABLE 5. Optical constants of the Yerkes 3× tank telescope.

Lens	Function	Outside diameter (in.)	Radii		Thickness (in.)	Space (in.)	Glass type
1	Objective	1.25	2.549	−3.053	0.26	0.346	DBC-3
2	Objective	1.25	−1.050	1.951	0.10	0.348	DF-1
3	Objective	1.25	6.92	−1.080	0.32	4.170	BSC-2
4	Collective	1.76	flat	−2.47	0.30	5.607	EDF-3
5	Erector	1.60	15.1	1.739	0.13	0.250	EDF-1
6	Erector	1.60	2.162	−4.087	0.33	1.797	DBC-2
7	Erector	1.76	−71.4	2.208	0.13	0.310	EDF-1
8	Erector	1.76	3.361	−2.778	0.42	7.737*	DBC-3
	Reticle	2.00	flat	flat	0.20	0.5†	BSC-2
9	Field	2.30	−3.982	1.600	0.12	cemented	DF-3
10	Field	2.30	1.600	−2.111	1.00	0.01	DBC-1
11	Center	2.30	9.29	−3.189	0.37	0.01	DBC-1
12	Eye lens	2.03	3.663	−1.942	0.55	cemented	DBC-1
13	Eye lens	2.03	−1.942	−9.38	0.12	1.2‡	EDF-1

* Adjust to focus on reticle.
† Adjust to focus eyepiece.
‡ Mean eye relief.

TABLE 6. Optical performance of the T 14.64 and T-93 tank telescopes.

Ray height (in.)	Color	Axial (mils) T-14.64	Axial (mils) T-93	Full field (mils) T-14.64	Full field (mils) T-93
0.42	C	−0.5	...	...	...
	D	0.4	−5.0	−7.0	−3.2
	F	−0.5	−8.7	−12.8	...
0.21	D	−0.2	2.5	0.0	−1.4
	F	...	1.6	...	...
0	D	0.0	0.0	0.0	0.0
−0.21	D	0.2	−2.5	2.5	21.6
	F	...	−1.6	...	...
−0.42	C	0.5	...	...	...
	D	−0.4	5.0	7.3	257
	F	0.5	8.7	−1.7	...
Accommodation (diopters)		3.2	0.6	0.0	0.0
Distortion		49	...	...	−20

It is evident that the NDRC telescope constitutes a real improvement over the original Arsenal design, especially near the center of

accuracy of fire. In the speed and maneuver of battle the gunner should be distracted from his gunnery as little as possible. Consequently, it was proposed by Army Ordnance in February 1944 that a tank telescope should be constructed, having a 5× magnification in a limited portion of the field, and a 1.5× magnification over as large a field of view as practical.[7a]

Figure 19 shows the proposed NDRC design for such a telescope, as worked out under Contract OEMsr-1078. The objective, erecting system, and eyepiece are standard. The collective lens, however, consists of a simple positive lens with a central hole containing a telephoto-like magnifier. This inserted triplet system provides effective 5× magnification over a limited field, and has a virtual image plane coplanar with the image plane of the objective.

The field of view is divided as shown in Table 7.

TABLE 7. Characteristics of the bifocal bipower telescope.

	True field (degrees)	Apparent field (degrees)
5× magnification	0 to 1.5	0 to 7.5
Dark zone	1.5 to 7.5	7.5 to 11.2
1.5× magnification	7.5 to 20	11.2 to 30

The obscured zone in the apparent field arises from the vignetting of the small lenses, and hence does not have sharp boundaries. It is obvious that there must be a region of obscuration in the true field, even if the apparent field is continuous. Because this factor is a serious one, no final design was attempted.

10.4.4 The Split-Field Tank Telescope

In order to overcome the difficulty of obscuration of part of the field present in the preceding design, it was proposed by the Ordnance Department that a split-field telescope of two

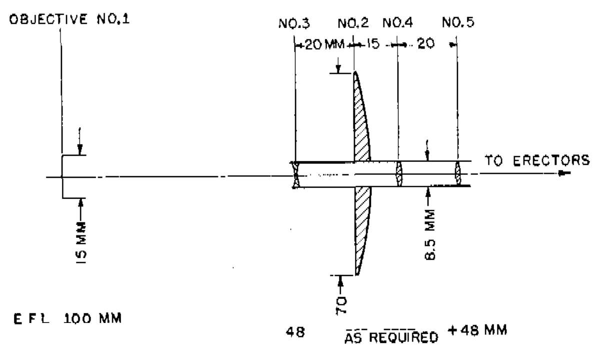


FIGURE 19. Magnifying system for differential magnifier in bipower telescope.

powers be constructed. It was believed that the usual apparent circular field of the individual telescope could be divided into two equal halves, the upper operating at 5×, the lower at 1.5×. Instead of dividing the fields for continuity at the common border, it was believed more practical to make use of two separate optical axes intersecting the respective fields at their centroids. Thus, an object like a tank would appear in the centroid of each field simultaneously at the respective magnifications.[7b]

Figure 20 shows the cross section of the optical design. The two objectives are telephoto and inverted telephoto, respectively, in order that coplanar focal planes might be achieved at two magnifications. The semicircular field lenses together make up a complete circle central in the tube. These semicircles are cut from a centered lens system, relative to the individual optical axes. Consequently, the two entrance pupils are imaged at infinity with the chief rays parallel to the optical axis of the entire instrument.

The second collective re-images the pair onto the entrance pupil of the erector system, and thence through the eyepiece. The final exit pupil is therefore circular and coincident without loss of light. The rays through this exit pupil from the two halves of the field differ in angle rather than position.

The general specifications of the single test model made up under Contract OEMsr-1078 are given in Table 8. The single test model was demonstrated and delivered to Army Ordnance.

TABLE 8. Characteristics of the split-field telescope.

Magnifications	5× and 1.5×
Number of lenses	19
Length	27.5 in.
Tube	2.75 outside diameter (up to eyepiece)
Exit pupil	5 mm round and centered on axis
Eye relief	1.6 in.
Apparent field	65 degrees
True fields	
1.5×	20 degrees radius
	40 degrees diameter along cut
5×	6 degrees radius
	12 degrees diameter along cut

Aberrations of the Split-Field Tank Telescope. The calculation of such a lens system presents problems. The multiplicity of optical axes and lack of rotational symmetry mean that individual parts of the system must be highly corrected for best results. Zero field in the objectives corresponds to about half field in the eyepiece. Fortunately, the telephoto objectives are well adapted to highly corrected fields, and at the same time for parfocal objectives having entrance pupils in the optimum location.

The eyepiece is approximately of the orthoscopic type with a large field free from astigma-

tism and with good eye relief. Such an eyepiece has a fairly pronounced curvature of field, but when used with the split-field telescope the trouble was not marked.

Table 9 gives the calculated aberrations of

TABLE 9. Aberrations of the split-field tank telescope at full field (mils in image space).

Aperture (mm)	Color	Erectors and eyepiece	5× objective	1.5× objective
2.50	D	—1.2	0.2	3.8
1.25	D	—0.1	—0.1	1.8
0.00	C	1.1	...	...
	D	0.0	0.0	0.0
—1.25	D	—0.5	—0.1	—0.5
—2.50	D	—1.7	—0.7	4.6

out departing appreciably from the 5× optical system. It was planned to place the 1.5× field above, and the 5× below. Contrary to the field arrangement of the first split-field design, the 5× field had its optical axis unaltered in the center of the apparent field, and on the division line. The optical axis of the 1.5× field, however, lay at the centroid of the upper half of the apparent field. The true fields for the 1.5× were 20 degrees along the cut and 10 degrees up and down, and for the 5×, 6 degrees along the cut and 3 degrees up and down.

The T-118 telescope made use of a 4-mirror erecting system. The modification into the split-field form unfortunately required separate mirror erectors and separate objectives.

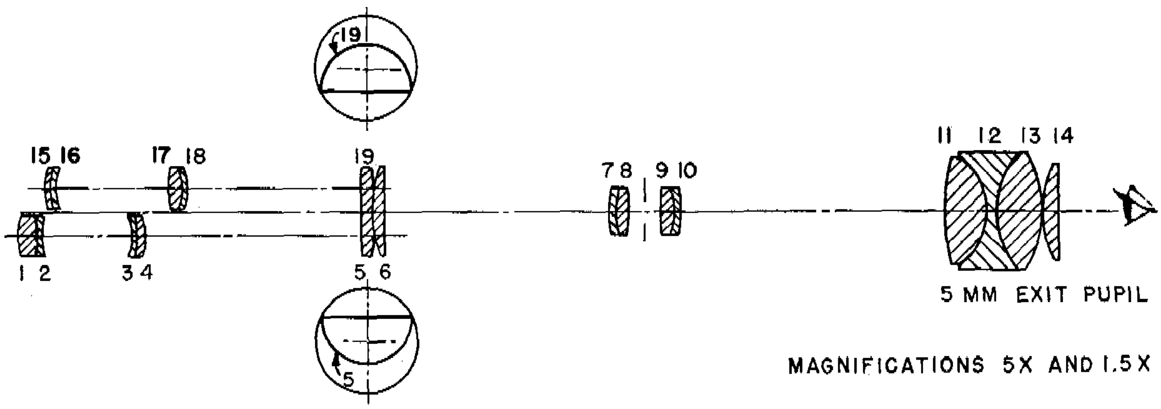


FIGURE 20. Optical system of split-field telescope.

the system. For more complete tabulation the reader is referred to the original report.[7]

10.5 ANTITANK TELESCOPE

The T-118 antitank telescope developed by the Polaroid Corporation was designed for very large exit pupil and eye relief.[7c] The system measured 20x7x7 in. and used an objective 4 in. in diameter at 5× overall magnification. The T-118 model employed plastic lenses, with the exception of one glass protective lens. The optical properties include an exit pupil of 20 mm, a true field of 6 degrees, an apparent field of 30 degrees, and an eye relief of 4 in.

The purpose of the modification developed at Yerkes under Contract OEMsr-1078 was to produce a split-field telescope of 1.5× and 5× with-

The 1.5× objectives consisted of an inverted telephoto lens, covering a 20-degree field at $f/5$. The two separate optical systems form separate images on the two semicircular coplanar reticles required. The eyepiece shows both fields simultaneously. The reticle contains two patterns, one for each field of view. The two exit pupils coincide.

Two objectives were designed, ITP-12 and PL 11, the latter containing plastic elements with the exception of the protecting front element.

Eccentric Collective. Since it was undesirable to alter the fundamental design of the 5× side of the field, the optical axis of that objective was left coincident with that of the eyepiece. However, the 1.5× objective was placed so that its optical axis lay 0.55 in. above the

axis of the eyepiece. Since the entrance pupil of the 1.5× was therefore centered 0.55 in. above the axis of the eyepiece, the closer to the eyepiece, the otherwise uncorrected exit pupil would have been below that of the 5× by 0.1 in. and about 0.8 in. to the right. This disadvantage was overcome by making use of an eccentric collective, which combined prismatic effect and power to readjust the pupil. The exit pupils of the two final systems were therefore perfectly coincident.

Table 10 gives the computed aberrations of the ITP-12 objective.

TABLE 10. Aberrations of ITP-12 objective in mils in image space.

Aperture (in.)	Color	Axial	Half field	Full field
0.4	D	—0.1	0.5	0.4 (vignetted)
	F	—0.1	...	...
0.2	D	0.1	0.2	0.1
0.0	D	0.0	0.0	0.0
—0.2	D	—0.1	—0.3	—0.2
—0.4	D	0.1	0.2	1.3 (vignetted)

10.6 SPECIAL BINOCULARS

At the request of the Army Ordnance Department a periscopic binocular was developed under Contract OEMsr-160 for use by tank commanders.[8] This instrument has 7× magnification and a 10-degree real field. The binoculars have 7-mm exit pupils, and long eye relief, so that they are usable under unfavorable lighting conditions and under conditions of considerable shock. A number of unusual mechanical requirements were met, including provision for quick replacement in the field of the top prism system which is exposed to destruction by shell fire.

Substantial production of 7x50 wide-field instruments was undertaken by Army Ordnance. The production was very considerably modified, however, to include a small unit-power system as well. This unit-power system had been included in the original design of the Institute of Optics, but was removed on Army request. It was later reinstated after further designs and samples were submitted. The entire program began in November 1942.

Under Contract OEMsr-579 the Bausch and Lomb Optical Company delivered a 7x50 binocular to be attached to a special device on the deck of a submarine.[4a] This binocular was built to withstand a pressure of 200 psi without damage that would prevent subsequent surface use.

Also under Contract OEMsr-579 the Bausch and Lomb Optical Company delivered one sample each of a standard 6x30 and a 7x50 glass equipped with nonfocusing eyepieces.[4b] It was believed that since most military users had normal or nearly normal eyesight, fixed focus binoculars would not only prove practicable but would lead to simplifications in construction and to reducing water ingress and other contamination.

10.6.1 The University of Rochester Periscopic Binoculars for Tank Commanders

A 7× binocular with an 8-in. vertical offset between the horizontal optical axes of the objectives and the eyepieces was required. It was also required that the binoculars have 7-mm exit pupils, a 10-degree real field, and a large eye relief. Image quality was to match that of the standard 7x50 hand-held glass. Mechanical requirements stipulated a 12-degree minimum angle of depression and a 20-degree upward tilt, an interpupillary distance adjustable from 58 to 72 mm, an eyepiece adjustable for focus in a range of 5 diopters on either side of infinity focus, and adjustments for alignment. All exposed parts were to be covered with plastic and were to be easily replaceable. Space between the objectives was to be provided for a unit-power rear vision or forward viewing optical system.

The system adopted is shown in Figure 21. A modified Porro prism system was used for image erection with the entrance prism split to leave 8 in. between the first and second reflection for the periscope offset, and the objectives placed between the two parts of the prism. In order to allow for passage of the oblique rays with little vignetting, the prisms were made

very large. The optical system proved to give better image quality than that of the standard 7x50 binoculars. All other requirements of the

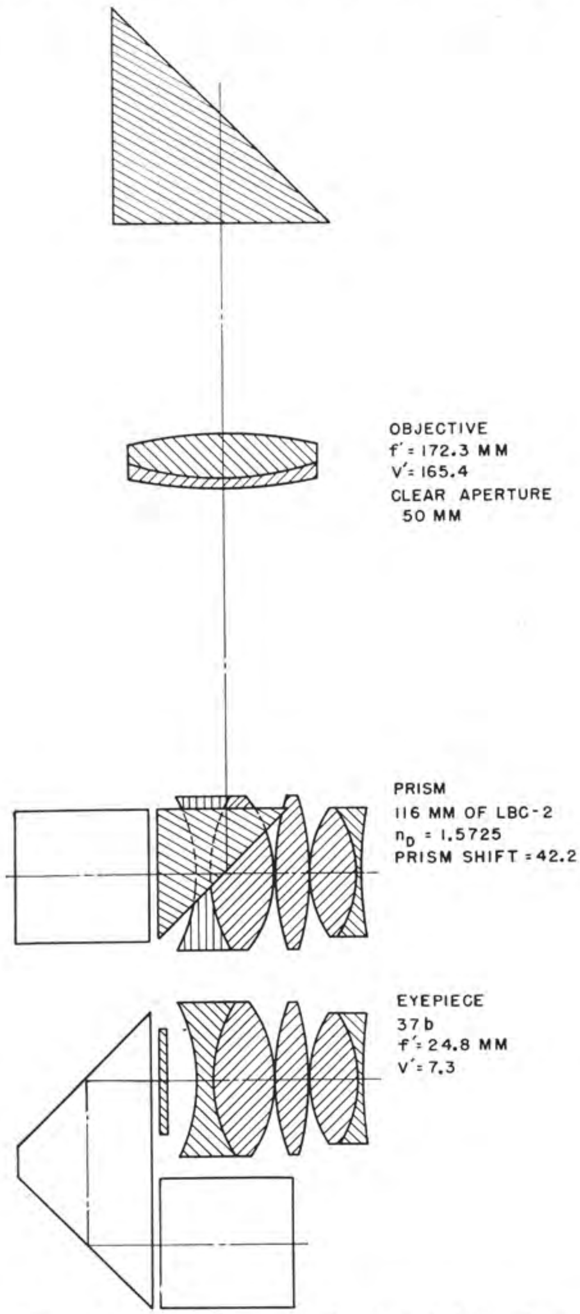


FIGURE 21. Optical system of periscopic binoculars.

device were met in the mounting. Figure 22 shows a view of the completed instrument.

Extensive optical tests were made on the system. The most noticeable defect in the image quality proved to be the rapid deterioration near the edge of the field. Comparison with a 7x50 Zeiss showed that the NDRC periscope binoculars were as good out to the full field.

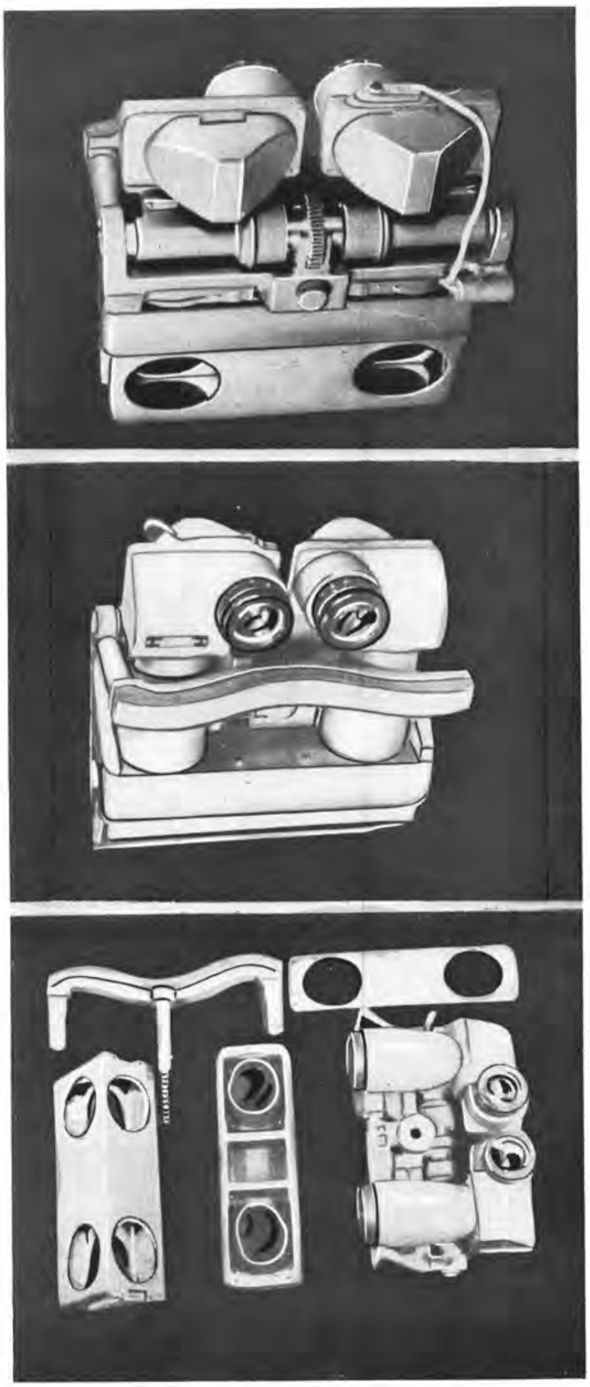


FIGURE 22. T-9 periscope binoculars.

Field tests by the Army at Fort Knox brought forth a number of minor difficulties, all

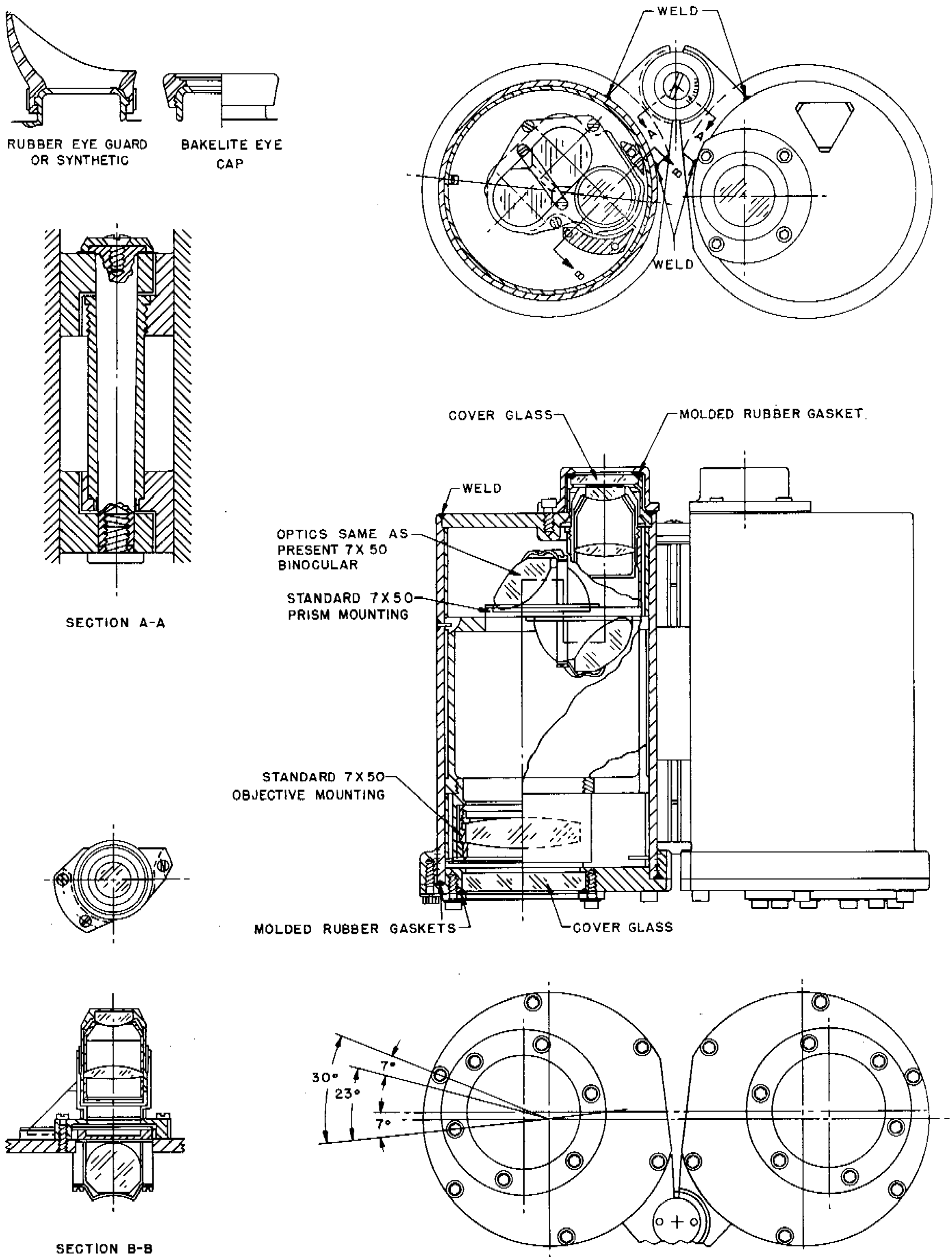


FIGURE 23. 7x50 pressureproof binoculars.

of which were overcome by slight alterations in design. A corresponding Arsenal model was put into production during 1944.

10.6.2 Bausch and Lomb Pressureproof Binoculars

The task of pressurizing the 7x50 binoculars was entirely a mechanical problem. For the sake of simplicity and speed of delivery, the eyepieces were of fixed focus. Figure 23 shows a sketch of the instrument. The jacket consists of a cylinder closed at the eyepiece and by a cover welded into a recess in the main jacket. This cover carried a hood for the mounted eyepiece which terminated in a cover glass sealed in with a suitable gasket. The objective end of the jacket was also closed by a cover, likewise sealed to the jacket by a gasket and held in place by a number of screws. This cover in turn contained a thick cover glass sealed in with a gasket. This construction permitted insertion of the optical parts, which were mounted on a skeleton framework of cast iron.

The jacket and associated exposed parts of the sample binocular were made of mild steel. In production it was intended to make use of stainless steel to resist the corrosive sea.

Tests. Since the optical system was standard, no tests other than pressure tests were conducted. The tests proved that the binoculars could withstand the pressure limit assigned without suffering permanent injury to the performance.

10.6.3 Fixed-Focus Binoculars

The problems met by the Bausch and Lomb fixed-focus binoculars were: (1) adjustment of the eyepiece to a predetermined number of diopters plus or minus relative to the position of infinity focus, (2) reliable clamping in this position, (3) adjustment of the eyepiece to some other position in case of repair or other need, and (4) water-tightness.

Figure 24 shows two views of the fixed-focus eyepiece. The simplifications achieved in production would have lowered the cost of the binoculars by only $1.50 without greatly accelerating output. However, the physical advantages offered by the simplification might be worth while.

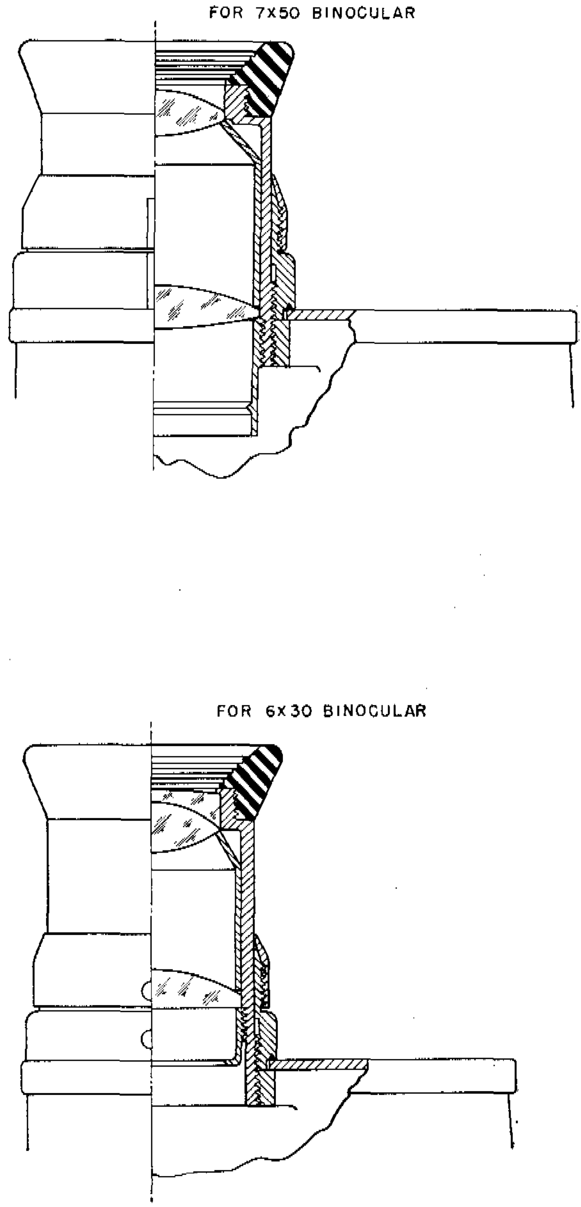


FIGURE 24. Fixed-focus eyepieces.

Final delivery of the 6x30 and 7x50 coated binoculars with eyepieces set for —0.75 D was made in July 1943 to NDRC.

10.7 OPTICAL DESIGN WITH PLASTICS

Optical design work on plastic optics carried out at the Polaroid Corporation was very extensive.[9] In most instances it was found that

[redacted]

design problems were greatly complicated by the absence of a variety of optical properties and the unsuitability for many applications of the indices of the plastics available. In addition,

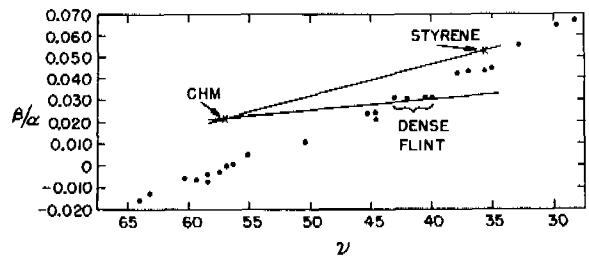


FIGURE 25. Optical constants of glasses and plastics.

there were a number of practical considerations that limited the scope of the designs. Among these were change of focus with temperature, bubbles, scattering, surface changes on molding, and quality of surface.

The optical constants of CHM ($n_D^{20} = 1.5064$, $\nu = 56.9$) and of styrene ($n_D^{20} = 1.5916$, $\nu = 31.0$) are adequate for the design of ordinary visual instruments. Figure 25 shows the index for the D line plotted against ν for representative optical glasses. The positions of CHM, styrene, and EDM are also shown. CHM-styrene pairs are "old glass" combinations and therefore do not yield the advantages of some of the "new glass" combinations.

Styrene has in its favor an unusually low ν-value for its index. For many purposes achromatization with styrene leads to rather shallow curves, which properly used may reduce higher order aberrations otherwise accentuated by the relatively low indices of the two materials. CHM has in its favor unusual properties for reduction of secondary spectrum. Combined with styrene, a CHM objective will have about two-thirds of the secondary spectrum of a normal glass pair. Combined with dense flint, CHM will remove nearly all of the secondary spectrum.

The Polaroid report[9] states that while the CHM-styrene combination is comparable to an ordinary glass pair for the design of visual instruments, plastic combinations are not as satisfactory for the design of camera lenses. A plastic with high ν-value and high index was sought at great length without material success. Consequently, resort was made to combinations of glass and plastic.

Reflector Aerial Gunsights. Certain designs do not require a lens with flat field but do require lenses with a low ratio of overall length to clear aperture. Such a lens is desirable for reflector gunsights. A material with low ν-value leads to feasible achromatization with shallow curves. Without this low ν-value, the lens curvatures are so steep that, to obtain sufficiently clear aperture for the lens system, the lenses themselves must be thicker than the desired overall length. Ideally, a plastic or other material with ν-value lower than 25 is desirable.

Wide-Angle Eyepieces. In the design of wide-angle eyepieces it is desirable to achromatize with shallow curves so that aberrations do not become excessive. A low ν-value makes this possible. A plastic material is required that possesses a ν-value considerably below 25.

Under Contract OEMsr-70 Polaroid undertook development of plastics with unusually low ν-values. Although several such materials were synthesized, production in large quantities would have been handicapped by the extra steps required, compared to CHM. It is believed that if the demand for a high-index material of low ν-value proves sufficiently great, small-scale production can be accomplished.

10.7.1 Athermalization

The changes in volume and index of refraction with temperature of plastic materials are large. The position of the focal surface of a lens system of plastic therefore depends markedly on temperature. In military instruments it is often inconvenient or impossible to adjust focus for any cause. Consequently, steps were taken at Polaroid to develop plastic systems with stabilized thermal properties. The main conclusions are as follows:

1. Athermalization can be accomplished in a plastic system by the addition to the lens system of one or more glass lenses which have a negligibly low coefficient of thermal expansion.

2. It is possible to athermalize a plastic system by using a housing composed of alternate sections of metal and plastic. The effect of a cumulative contraction adequately compensates

for changes in the elements. The procedure of compensation analogous to that of a compensated pendulum can also be effected.

3. Partial athermalization for focal distance can be obtained quite simply by using an aluminum housing. In a telescope with plastic elements housed in an aluminum tube, a temperature drop would reduce the back focal distance of an element, while at the same time the aluminum tube would undergo a compensating contraction.

4. A plastic mirror system may be completely athermalized by making the connection between the mirrors, and from the mirror to the focal surface, of the same plastic material as the mirror. This is also essentially true of a system like the Schmidt where the refracting element has negligible power.

The thermal correction of an optical system is very analogous to the usual chromatic correction. The constant ν as defined from the dispersion of a glass and its index is replaced by a quantity ν_T, also characteristic of the material. This ν_T is used in the same fashion. An athermal system requires that the ν_T's of the two materials differ widely if athermalization is to be achieved. The report[9] states that for plastic materials known at present, the ν_T's differ only slightly.

To athermalize a system one or more glass lens elements must be introduced, the glass serving as the thermal crown, and the plastic as the thermal flint. The ν_T for glass is approximately 10 times that for plastic. Athermalization can be accomplished by using a single element of glass as the outside lens of the system in order to serve as protection for the plastic elements. A glass element is chosen whose focal length is approximately the same as that of the whole system. One example of a well athermalized system, in the absence of temperature gradients, is the objective lens of the T-108 telescope.

10.8 PRECISION THEODOLITE TELESCOPES

The Army Engineer Board requested NDRC through the University of Rochester to design a compact internal focusing telescope of the highest possible optical performance for use in production of a precision theodolite.[10]

The optical specifications for the telescope were as follows:

1. The objective was to be of 1.5 in. aperture.
2. The eyepiece was to yield a large field of view and have an eye distance greater than 0.33 in.
3. The telescope was to be inverting, and to focus internally. The overall length was not to exceed 7½ in.
4. The system was to be free of scattered light.
5. The exit pupil was to exceed 0.06 in.
6. The magnification was to be 25 to 30×. The system was to be sensibly free from spherical aberration, chromatic aberration, astigmatism, coma, curvature, and distortion.
7. The resolving power was to be 4 sec of arc or better.
8. The minimum sighting distance was to be 10 ft.
9. The telescope was to be anallatic so that stadia might be read within 1 ft at all distances exceeding 10 ft.

Four foreign theodolite telescopes of high quality were sent to the University of Rochester for tests. It was requested that the new telescope equal or exceed the optical performance of the best of these. The four types received were:

1. C.T.S.[b] level (41730)
2. Tavistock T-65 (39481)
3. Zeiss II (Nr 34174)
4. Wild T-2 (7158)

Inasmuch as the eyepiece in the theodolite works at very moderate aperture, the overall performance of the telescope is largely dependent on the objective. Tests were made in which the eyepiece was replaced by a 100× microscope. The telescope was directed toward a distant point-source, and studied first through a monochromatic green filter, and then without filter.

These tests showed that the best results were achieved with the C.T.S. level and Tavistock, but that the Zeiss theodolite offered the most practical design. The variations from perfection appeared to be due mostly to manufactur-

[b] Cooke, Troughton, and Simms (Optical firm in York, England).

ing difficulties. Accordingly, the final specifications were to design a telescope with dimensions similar to the Zeiss instrument and with optical performance equal or better. Only optical glasses of American manufacture were to be employed. The number of glass-air surfaces was to be the same or fewer, compared to the Zeiss system.

Design. The final design contains a triplet air-spaced objective, focal length 122 mm, with an effective aperture of 40 mm. The focusing is done with an internal negative lens of focal length −47.6 mm. This lens is made a separated doublet with positive and negative crown elements. The eyepiece is a standard orthoscopic.

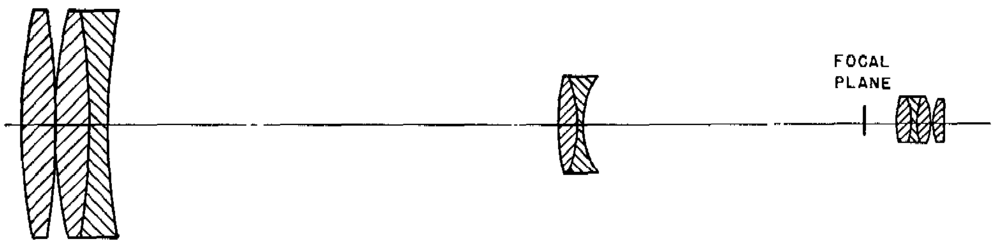


FIGURE 26. Optical system of theodolite.

The three separate parts of the theodolite must be corrected individually for the pertinent aberrations. Even though the design may be sufficiently perfect theoretically, it presents a manufacturing problem of considerable magnitude. The optical system collectively must meet the Rayleigh tolerance.

The final optical characteristics of the telescope were:

1. Magnifying power, 27.2.
2. Exit pupil, 1.47 mm or 0.058 in.
3. Real total field, 1.5 degrees.
4. The telescope is anallatic to 1 per cent from 3 m to infinity.
5. Overall length of the optical system, 6.5 in.

A sample was made up by the W. and L. E. Gurley Company. After a number of tests, and two modifications of the sample, a sufficiently good model was obtained. The original sample submitted was undercorrected spherically by 6 times the Rayleigh limit. The reworked model was still undercorrected slightly, due apparently to slight turned edges. A final slight change of design produced a bit of overcorrection. The observed angular resolution was very close to the theoretical requirements and equal to or better than the Zeiss resolution.

Although in the early tests the Zeiss instrument excelled for freedom from scattered light, the NDRC telescope after thorough internal blackening and light trapping proved to be equal or superior to the Zeiss instrument in this respect. A further small change was made in the eyepiece in order to obtain a colorless and sharply defined field stop. Figure 26 shows a cross section of the final optical system.

The theodolite telescopes were later manufactured in large quantities for use with the theodolites manufactured by the Gurley Company.

10.9 SUBMARINE PERISCOPES

The problems raised by the Eastman report (see reference 1 in Chapter 18) on periscope photography were brought to the attention of the Yerkes Optical Bureau under Contract OEMsr-1078 for study and possible solution.[11] These problems were threefold: (1) secondary color, (2) larger eye relief, and (3) curvature of field. Altogether, three existing Kollmorgen periscopes were investigated. It is stated that a completely new design would have made it easier to correct troubles, and that only limited improvements could be made in the existing designs.

10.9.1 Improved Periscope Design

The properties of the existing Kollmorgen periscopes are listed in Table 11. The designation N refers to the number of elements and D to the diameter of the top part of the periscope

tube. All these periscopes are provided with magnifications of 6× and 1.5× the latter by insertion of an inverted Galilean telescope before the top objective. Photographic work is accomplished exclusively with the 6×. The diameter of the true field of view is 8 degrees, the apparent field 48 degrees. The length of tube is 40 ft. All systems have considerable vignetting of the exit pupil near the edge of the field. Type 1.4 is the most used, but also the most complex.

TABLE 11. Properties of the Kollmorgen periscopes.

Type	N	D (mm)	Exit pupil (mm)
1.4	19	44	4
1.9	10	44	4
IV	10	76	7

Aberrations of the Three Periscopes. The existing imperfections of the periscopes listed above were determined by ray tracing. In the following tables (Tables 12, 13, 14) depicting the results, a refers to the intercept of the individual ray in the exit pupil, as measured from the optical axis in a perpendicular direction for a fixed position of the exit pupil. The angle U refers to the off-axis field angle of the principal ray in object space. The aberrations are given in terms of mils in image space of the computed ray's direction, referred to the principal ray. Curvature of field is not taken out, since the purpose of the investigation is photographic rather than visual.

TABLE 12. Aberrations of the type 1.4 periscope (mils).

Color	*Axial,* $U_1 = 0°$ $a = 1.0$ mm	$a = 1.5$ mm	$a = 2.0$ mm
C	0.3	0.7	1.7
D	1.0	1.8	3.0
F	0.1	0.2	0.0
g		—5.1	
h	—7.6	—12.1	—17.5

Color	*Off-axis* a (mm)	Half field $U_1 = 2°$	Three-fourths field $U_1 = 3°$
F	1.0	1.0	0.7
F	0.0	0.0	0.0
h	0.0	0.9	
F	—1.0	—0.7	—1.2

Adopted entrance pupil, 170 mm in front of first lens.

TABLE 13. Aberrations of the type 1.9 periscope (mils).

Color	*Axial,* $U_1 = 0°$ $a = 1.0$ mm	$a = 1.5$ mm	$a = 2.0$ mm
C	—0.1	0.0	0.4
D		0.5	
F	—0.2	—0.2	0.1
G′		—3.1	
h	—4.1	—6.1	—8.2

Color	*Off-axis* a (mm)	Three-fourths field $U_1 = 3°$
F	0.67	—0.6
F	0.33	—0.2
F	0.00	0.0
F	—0.33	0.3
F	—0.67	0.5

Adopted entrance pupil, 230 mm in front of first lens.

TABLE 14. Aberrations of the type IV periscope (mils).

Color	*Axial,* $U_1 = 0°$ $a = 1.75$ mm	$a = 2.62$ mm	$a = 3.50$ mm
C	0.9	1.5	2.9
D		1.8	
F	0.0	0.0	0.2
G′		—3.7	
h	—5.1	—7.9	—10.6

Color	*Off-axis* a (mm)	Three-fourths field $U_1 = 3°$
F	1.75	—0.7
F	0.88	—0.6
F	0.0	0.0
h	0.0	2.8
F	—0.88	0.6

Adopted entrance pupil, 290 mm in front of first lens.

SECONDARY COLOR AND ITS CORRECTION

An investigation was made of correction of secondary color for periscope purposes. The problem required substitution of at least a triplet objective in order to meet all requirements of focal length, and full color correction. Even with a fluorite, BSC-1 and EDF-2 combination, it proved necessary to use more than three elements in order to reduce the large lens powers. It was necessary to introduce overcorrected secondary color in the objective in order to reduce the secondary color of the system as a whole.

Type 1.4 Periscope with the P-55 Fluorite Corrector. The Yerkes report[11] states that one-

[redacted]

third of the secondary color of the type 1.4 periscope arises in each of the two large doublets, while the remaining one-third arises in all the other lenses. It was believed that any attempt to remove the color aberrations should be for 100 per cent correction. Anything less was believed to reduce the loss of contrast at the expense of loss of definition, until some small value of the circle of confusion had been reached.

Only two reasonable possibilities existed for elimination of the color aberrations. The first of these involved the insertion of a zero-power correcting combination between the large doublets at the point where the ray height reached a maximum. The early calculations showed, however, that even at the optimum location, success was exceedingly doubtful. The second possibility involved replacing one of the large doublets by a correcting lens of equal power, but overcorrected color. This second possibility was pursued.

Many computations were required before a result satisfactory from all points of view was obtained. Methods were developed for complete control over the spherical aberration, the zonal spherical, the paraxial color, chromatic variation of spherical aberration, and the coma. The final residual aberrations were even balanced

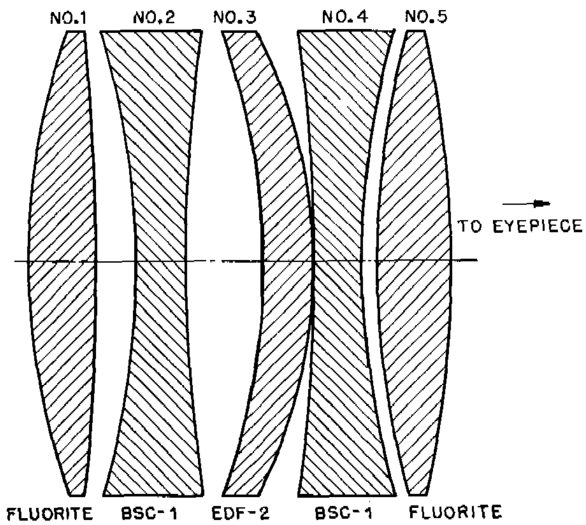


FIGURE 27. P-55 fluorite corrector for type 1.4 periscope.

for secondary color variation in the spherical aberration. Figure 27 and Table 15 contain the final specifications for the fluorite corrector. It should be noted that the aberrations of this corrector are magnified 30× in final image space. Hence, the effort put into the design work was very much worth while.

For similar reasons the construction work was critical. This work was carried out at the Harvard laboratory under Contract OEMsr-474.[12] In the Harvard report it is stated that the curves were held to better than one part in 2,000, that the thicknesses were held to less than 0.002 in. from assigned values, that the centering was satisfactory, and that the glass-air surfaces were figured individually to better than one-quarter wave. On the other hand, considerable difficulty was experienced with the fluorite-air surfaces of which there were four. The chief trouble lay in the occurrence of

TABLE 15. Optical data for P-55 fluorite corrector for type 1.4 Kollmorgen periscope.

Lens*	Radius (mm)	Separation or thickness (mm)	Material
1	163.1	17.0	fluorite
	—674.0	10.1	
2	—186.7	12.0	BSC-1
	368.6	20.0	
3	—154.0	12.0	EDF-2
	—121.6	0.02	
4	—414.7	12.1	BSC-1
	191.8	4.0	
5	229.9	18.0	fluorite
	—259.6	2,060.5	

* All lenses have 115 mm diameter.

numerous small pits at the center of minute depressions of fair diameter. These depressions were several fringes deep and as much as 1/8 in. in diameter. In addition, it was difficult to hold the surfaces spherical within several fringes. The final image of a star examined under 50× seemed somewhat diffuse.

Table 16 gives the results of ray tracing with the new corrector in place. The monochromatic performance is slightly inferior to the earlier design, but the color has been improved markedly. The off-axis performance is adversely affected by slight coma and lateral color introduced by the corrector. This lateral color is of a secondary nature, introduced by the refraction of principal rays through the corrector above the axis. To remove this lateral color,

both large doublets would have to be replaced, or else a corrector put at a pupillary point. In spite of the lateral color introduced, the off-axis chromatic performance is still much better than given by the original system.

Table 16. Aberrations of P-55 corrector with type 1.4 periscope (mils).

Color	*Axial*, $U_1 = 0°$ $a = 1.0$ mm	$a = 1.5$ mm	$a = 2.0$ mm
C	—0.1	0.4	0.8
F	0.1	0.5	—0.6
h	—0.4	0.1	0.9

Off-axis

Color	a (mm)	Half field $U_1 = 2°$
F	1.0	0.4
F	0.0	0.0
h	0.0	—5.1
F	—1.0	2.4

The Type 1.9 Periscope and the H-12 Corrector. This periscope differs from Type 1.4 in that it consists of but a single erecting telescope. Most of its secondary color arises in the two large erecting doublets, and it can be corrected most conveniently there. Consequently, it becomes possible to replace these doublets by fluorite, BSC-1 doublets with elimination of secondary color of the system. The EDF-2 element needed for the earlier corrector is not needed here, inasmuch as no overcorrection for secondary color is necessary. Table 17 contains the optical data for the Type 1.9 periscope redesigned doublets.

Table 17. Optical data for the H-12 fluorite corrector for the type 1.9 periscope.

Lens	Radius (mm)	Separation or thickness (mm)	Material	Outside diameter (mm)
1	plano	15.0	BSC-1	147
	523.8	4.0		
2	520.5	18.0	fluorite	147
	—692.1	7297.0		
3	692.1	15.0	fluorite	115
	—520.5	4.0		
4	—523.8	12.0	BSC-1	115
	plano	2027.0		

The lateral color of the corrected system is less than that of the original periscope design. Moreover, the axial performance is good over the entire range of colors. The doublets are fully corrected for color, spherical aberration, and coma. The required diameters, unfortunately, are at least 4.5 in., and one up to 5.8 in. would be desirable. However, it should be pointed out that provision of a good periscope system for so complex and expensive an object as a submarine cannot be ignored at any cost normal to optical applications.

Table 18 contains the results of ray tracing for the H-12 and Type 1.9 periscope, for axial and off-axis aberrations.

Table 18. Aberrations of H-12 corrector and type 1.9 periscope (mils in image space).

Color	*Axial*, $U_1 = 0°$ $a = 1.0$ mm	$a = 1.5$ mm	$a = 2.0$ mm
C	—0.4	—0.6	—0.7
D		—0.7	
F	—0.1	0.1	0.1
G′		0.2	
h	—0.2	—0.3	—0.1

Off-axis

Color	a (mm)	Three-fourths field $U_1 = 3°$
F	0.67	—0.2
F	0.33	—0.1
F	0.00	0.0
h	0.00	0.3
F	—0.33	0.2
F	—0.67	0.3

The Type IV Periscope with the G-8 Corrector. The corrector adopted for the Type IV periscope is exactly analogous to that used in the 1.9. For complete transmission of the 7-mm exit pupil, lens diameters of 6.0 in. are needed. The aberrations are given in Table 19. The large exit pupil causes slightly larger residual aberrations, such as chromatic difference of spherical aberration. The off-axis performance is good. The lateral color is absent. The difference between primary and secondary curvatures of field yields a uniformly illuminated oval disk measuring about 0.2x2.2 mils at three-fourths field.

Revised Eyepiece of Larger Eye Relief

In June 1945 a request was made by the Navy for revision of the eyepiece in the Type 1.4 periscope in order to provide 5 to 10 mm more eye distance. The eyepiece designed to fill this need can be used with or without the chro-

[redacted]

matic corrector. Where the original design employs a curved face on the prism, the redesign utilizes a flat prism face as shown in Figure 28. This modification alone produces 7.7 mm additional eye relief. The redesigned eyepiece has slightly more negative astigmatism and consequently a flatter mean field than that of the old eyepiece.

TABLE 19. Aberrations of G-8 corrector and type IV periscope (mils in image space).

		Axial	
Color	$a = 1.75$ mm	$a = 2.62$ mm	$a = 3.50$ mm
C	—0.6	—0.9	—0.6
D		—0.6	
F	—0.1	—0.3	—0.2
G′		—0.3	
h	—0.3	—0.7	—1.2
		Off-axis	
Color	a (mm)	Three-fourths field $U_1 = 3°$	
F	1.75	—1.2	
F	0.88	—0.3	
F	0.00	0.0	
h	0.00	0.2	
F	—0.88	1.0	

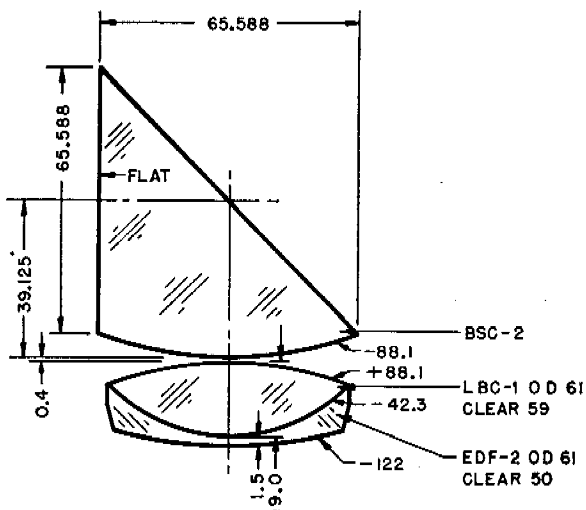


FIGURE 28. Type RE-4 eyepiece.

The calculations involved in the eyepiece design gave more information on the off-axis performance of the system for photographic use. The field is highly curved. For example, if a camera of 50-mm focal length is used, the confusion disk will be approximately 0.06x0.27 mm, owing mostly to errors in the secondary plane.

CORRECTION FOR FIELD CURVATURE

A great quantity of detailed information is contained in the Yerkes report[11] on field-flattening devices for the various periscopes. Space is too short to give more than a brief account.

It is possible to place a field-flattening lens in the primary focal plane of the periscope and to carry on photography with the eyepiece removed. The success of this arangement depends in practice on the optical quality of the periscope up to this point and on the curvature of field present. In the 1.4 periscope it is felt that such a field-flattening lens cannot be used. However, in the 1.9 type, its use is practicable.

The most successful device for improvement of periscope photography is the introduction of a new camera lens design called the PD-5. This lens is designed for use at $f/12$ and has a greatly overcorrected Petzval sum. By design of the camera lens it is possible to obtain a flat overall field of high correction for the entire field. Computation of the aberrations of the overall system show that a uniform image quality of 0.02 mm can be obtained over three-fourths of the field in F light by means of this

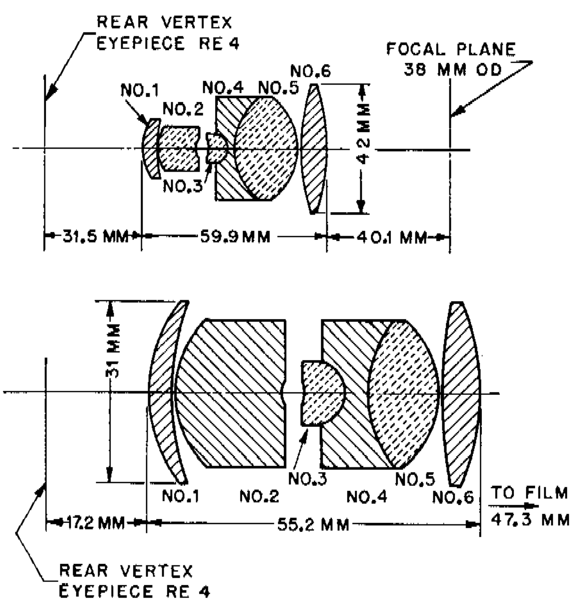


FIGURE 29. PD-5 and PC-60 field-flattening camera lenses.

special camera adapted to the 1.4 periscope. These results indicate a resolution of at least 25 lines per mm to be compared to the 16 lines per mm observed by Eastman investigators[11] at the center of the field.

Figure 29 shows a cross section of two such cameras designed for use with the 1.4 periscope. The PD-5 is for use with the original periscope and RE-4 eyepiece. The PC-60 lens is to be used with the periscope as modified by the P-55 corrector and RE-4 eyepiece. Apparently, the best performance in F light is given by the first mentioned combination, but over a range of colors, as in practice, the second combination is better. No tests have been made as yet with any of these combinations, and indeed, only the PD-5 prototype has been constructed.

Summary

Type 1.4 Periscope

P-55 Fluorite color corrector, replaces lower erector doublet.
RE-4 Eyepiece with longer eye relief.
PD-5 Camera lens for flat field with Type 1.4 periscope.
PC-60 Camera lens for flat field with Type 1.4 periscope and P-55 fluorite corrector.

Type 1.9 Periscope

H-12 Fluorite color corrector, replaces both erector doublets.
Field-flattening lens for standard camera with Type 1.4 periscope (only basic data for design).
Field-flattening lens for film before the eyepiece.

Type IV Periscope

G-8 Fluorite color corrector, replaces both erector doublets.
Field-flattening lens for standard camera with type 1.4 periscope (only basic data for design).
Field-flattening lens for film before the eyepiece.

Redesign of Submarine Periscopes

In the course of the development work under Contract OEMsr-1078, a number of general principles appeared that must be borne in mind in subsequent efforts.

1. In periscopes where the size of the top part of the tube is of paramount importance, it is still worth while to make the optical parts as large as possible for the assigned tube size. For example, the optical disadvantages of the Type 1.4 system are large compared to the Type 1.9, yet the objective lens sizes differ by only 10 mm.

2. In those periscopes containing one erecting telescope, 1.9 and IV, the use of fluorite apochromatic doublets is recommended. The objective need not use fluorite but could make good use of a flat field, as from a Cooke type of system. In any redesign of these periscopes, special attention should be paid to the location of the objective with respect to the top prism and to the sizes of the lenses for minimum vignetting.

3. A periscope with two complete telescopes like the 1.4 poses difficult design problems. If possible, the upper objectives and erectors should be redesigned with flat fields for photography in front of the eyepiece. If not, and if normal objectives with positive Petzval sums are used, they should still be redesigned with apochromats for freedom from secondary spectrum.

Photography with Type 1.4 redesigned will still require a special field-flattening camera like PD-5 after the eyepiece. Before the eyepiece, if the upper objectives have been carefully designed with flat fields, it may become possible to use a simple field-flattening lens.

4. Redesign of eyepieces with additional eye relief does not offer much difficulty.

5. Photography will be most efficacious through a periscope with the maximum possible exit pupil diameter in order to obtain short exposure times with cameras of long focal length. At present Type IV should use exposure times of about one-third of either Type 1.9 or 1.4. Vignetting should be minimized.

10.10 SPECIAL PERISCOPES

During the course of World War II need arose for a number of special periscopes either

for protection as in trench warfare, or for extending the field of the observer to otherwise inaccessible spots. This work was accomplished under Contract OEMsr-1078 at Yerkes and under Contract OEMsr-160 at the University of Rochester. Some of the construction work was carried out at Harvard under Contract OEMsr-474.

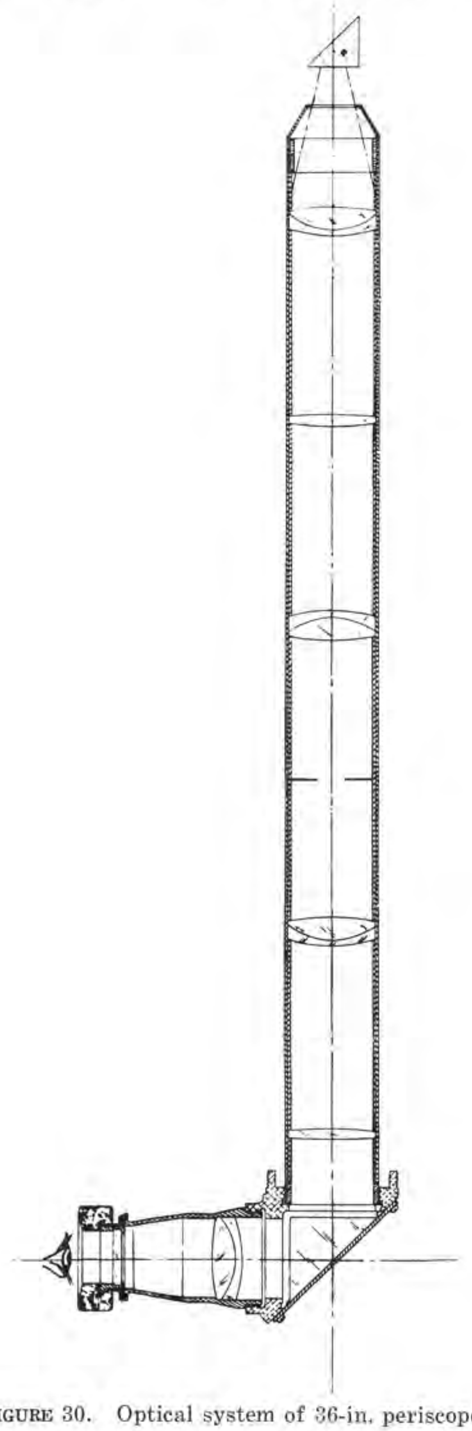


FIGURE 30. Optical system of 36-in. periscope.

10.10.1 Aircraft Periscope

In April 1944 a request was received (Project NR-111) from AsDevLant at Quonset Point, Rhode Island, to design and construct a unit-power periscope for the purpose of extending the view of the bombardier in the TBF-1 patrol plane. The periscopic sight was to be linked directly to a bombsight and searchlight for night patroling.

The optical design for the proposed periscope was undertaken at Yerkes and completed in a very short time.[13] The mechanical details were handled by the Harvard group in full cooperation with representatives of AsDevLant, who furnished the major portion of the design.[14]

Figure 30 shows a cross section of the final periscope design. Figures 31 to 34 show several views of the periscope in position in the airplane. Figures 35 to 40 show several views of the periscope with detailed indexing of the important parts.

FIGURE 31. View of AsDevLant periscope as installed in the TBF plane.

Optical Design. The requirements for the unit power periscope for AsDevLant were: (1) 24-degree total field, (2) large exit pupil, (3) large eye relief, and (4) an offset of 36 in. between the forward lines of sight at scanning prism and observer's eye.

[redacted]

The characteristic feature of the design is the use of cemented doublets placed at sufficient distances from the pupillary points to control the astigmatism. It was found that by proper choice of glass types it was possible to design a cemented doublet free from astigmatism.

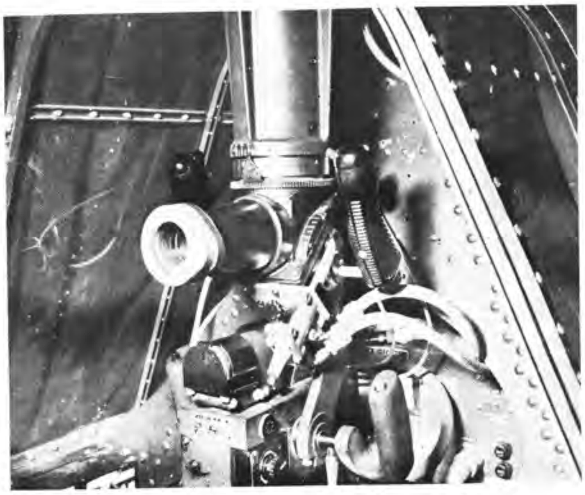


FIGURE 32. Cockpit view of AsDevLant periscope as installed in the TBF plane.

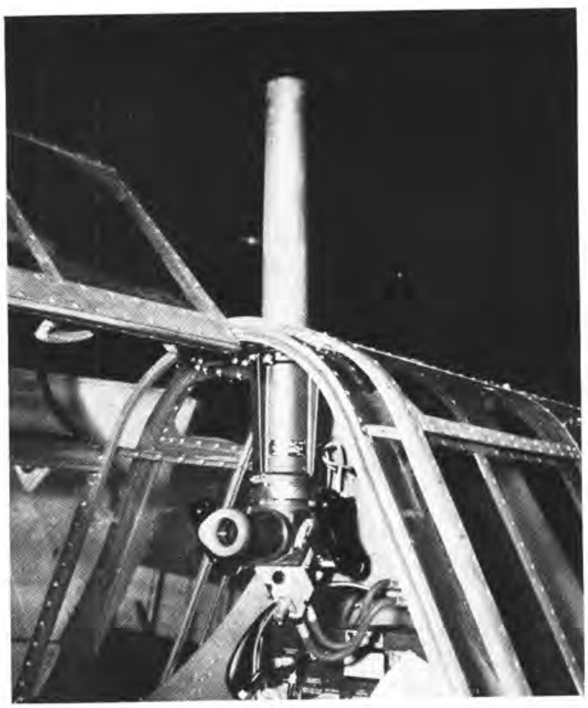


FIGURE 33. Cockpit view of AsDevLant periscope as installed in the TBF plane.

The upper prism of the 36-in. periscope was made large enough to permit scanning in elevation. The instrument as a whole rotated in azimuth. The final design shown in Figure 30 gives excellent definition over the entire field. The exit pupil is 0.8 in. in diameter, and the eye relief 0.4 in. Ten lenses were used with maximum diameter 2.5 in. The reticle was engraved on the back side of the collective lens in the

FIGURE 34. View of AsDevLant periscope in use by bombardier in the TBF plane.

form of a black interrupted cross and concentric circles. The curved rear side of the collective lens accommodated the calculated field curvature at that point.

The outstanding aberration of this unit-power system is unobjectionable spherical aberration off the optical axis. At full field there is a residual field curvature of only 0.3 diopters. At full field there is considerable difference between primary and secondary curvatures, but in view of the relatively small part of the exit pupil and the resultant reduction of the aberration disk, there is little effect on the sharpness of the image. The prototype showed no appreciable visual errors and left nothing

to be desired in performance. It is believed, however, that any future design should be based on a larger apparent field in order to facilitate use in the daytime. At night, the narrow beam of the searchlight required only a small field, and the boresighting of searchlight and periscope meant that the observer was always looking along the beam.

adjustment, waterproofing, and ease of operation. In all sixteen units were built and delivered to AsDevLant. Of this work NDRC contributed only the prototype complete and the optical parts of the remaining fifteen units. Service tests showed satisfactory results. The entire sixteen units were produced in the period from August to November 1944.

FIGURE 35. Assembly view of AsDevLant periscope.

FIGURE 36. Assembly view of AsDevLant periscope.

Mechanical Design. The prototype built in April and May 1944 proved to be satisfactory optically but lacked the necessary mechanical qualities for good linkage with bombsight, searchlight, and scanning prism. Representatives of AsDevLant prepared detailed drawings of a new mechanical design improved with respect to linkage, accuracy, facility of

The mechanical design consists of three main subassemblies: (1) the periscope optical system, (2) the housing unit, and (3) the control unit. The housing unit serves to protect the optical system and the mechanical parts. The upper end of the housing contains an elliptical window made of selected plate glass. The prism is mounted directly behind this window and is

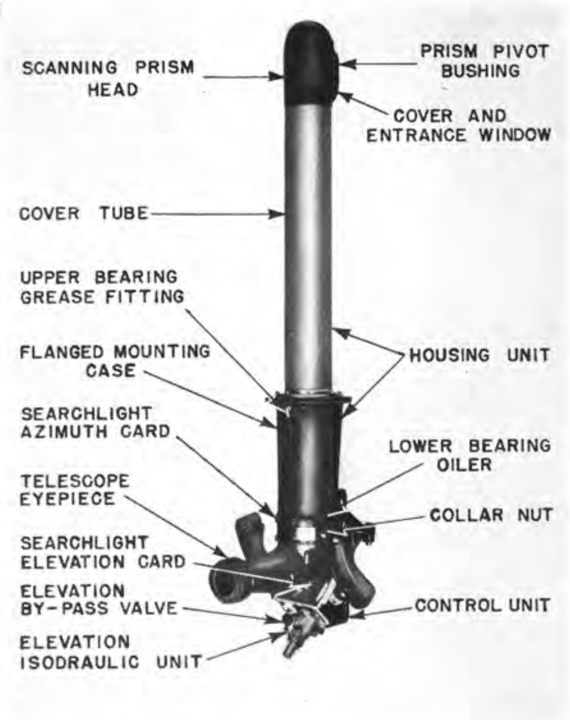


FIGURE 37. Detailing of AsDevLant periscope assembly.

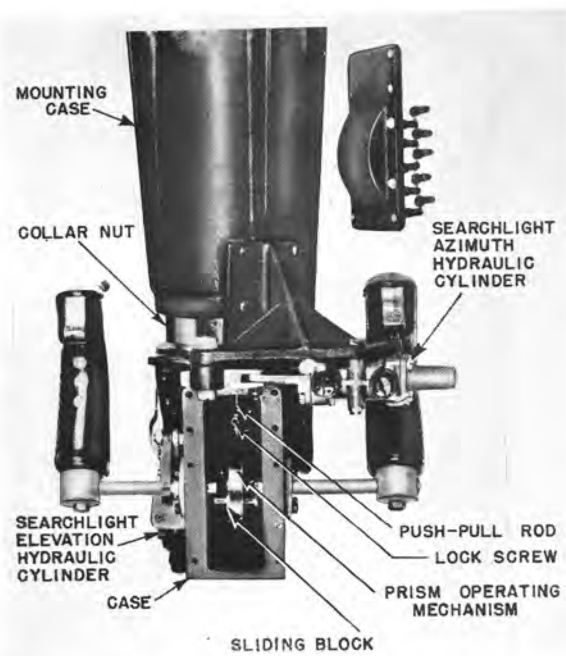


FIGURE 38. Detailing of AsDevLant periscope assembly.

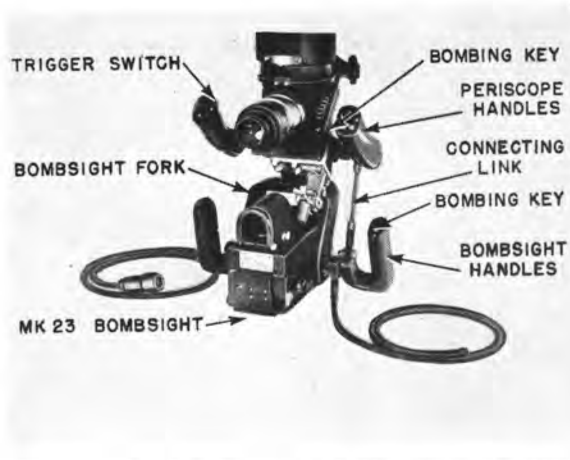


FIGURE 39. Detailing of AsDevLant periscope assembly.

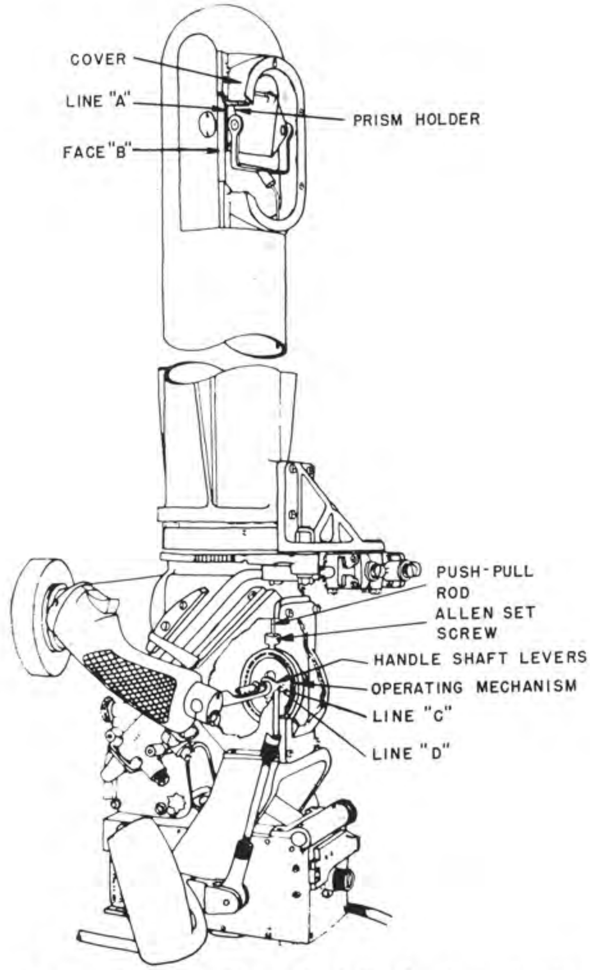


FIGURE 40. Detailing of AsDevLant periscope assembly.

[redacted]

operated from the handles 36 in. away by means of connecting rods. The rotation in azimuth is accomplished by swiveling the housing and interior unit in bearings housed in a casting with a flange that is bolted to the airplane.

The push-pull rod connecting the control unit below with the scanning prism passes between the outer housing and the tube of the periscope itself. In order to give the observer the convenience of "feeling" the elevation,

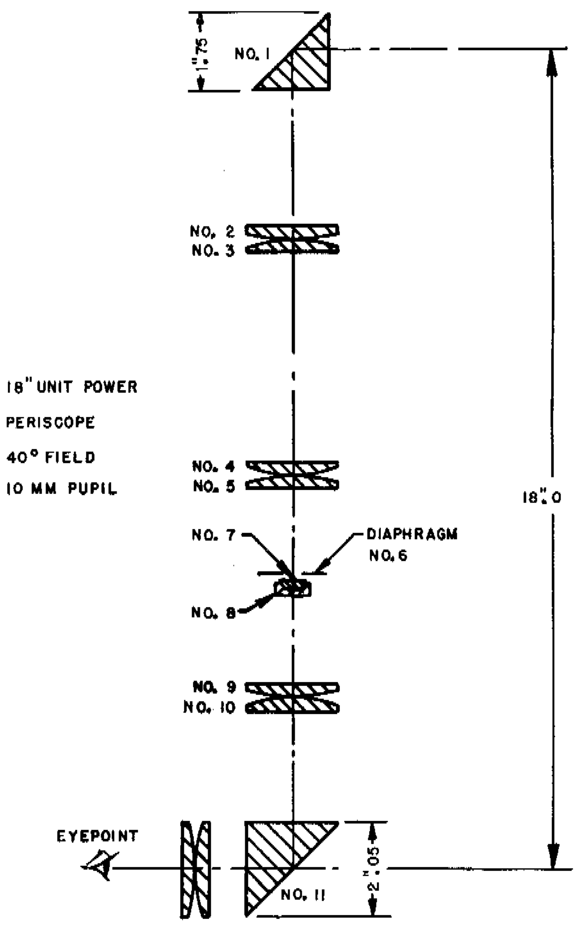


FIGURE 41. Foxhole periscope, Type 1.

there is a 2/1 reduction in rotation between the handle shaft and the upper prism which also allows for the factor of 2 in image shift versus prism shift in angle.

The control unit is connected by isodraulic remote control to the searchlight in the bottom of the ship. Any movement in elevation or azimuth will be transmitted directly to the searchlight. The searchlight is therefore always boresighted with respect to the cross wires of the periscope. The isodraulic units work independently in elevation and azimuth. The isodraulic unit itself has been worked out carefully to allow for contraction or expansion of the fluid in the cylinders and connecting tubes. Initial alignment is provided for by a by-pass valve, which allows one piston to be moved at one end of the unit without corresponding movement of the other piston.

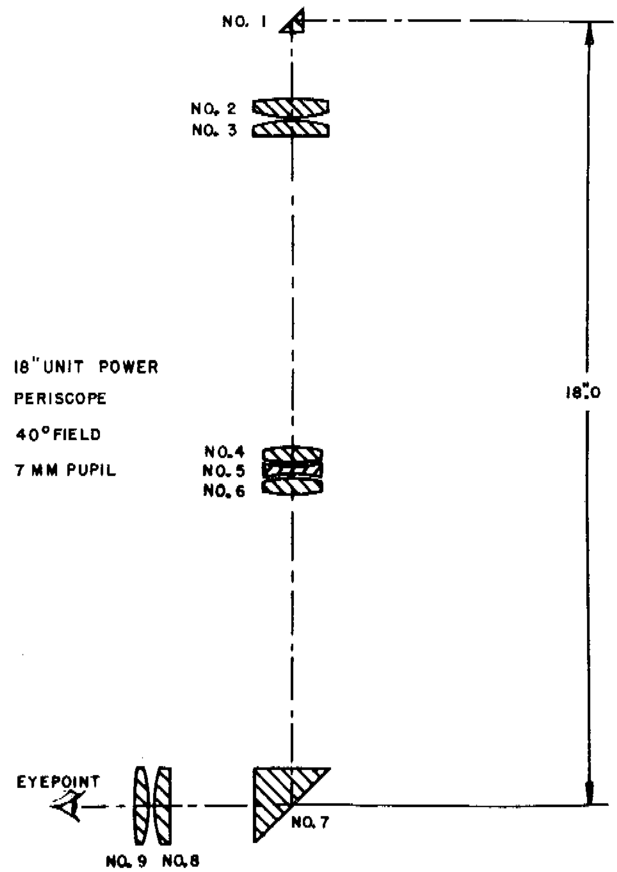


FIGURE 42. Foxhole periscope, Type 2.

A Mark 23 bombsight is installed on the lower end of the periscope. The bombsight comes with a pair of handles like the handles of the periscope. Operation of the periscope can be carried out with either pair of handles, arranged for by a direct connecting link. The bombsight handles are used for daytime bombing, and the periscope handles for a night searchlight attack. Bomb release is accom-

plished by either of the two right-hand handles. The searchlight switch is located only on the upper left-hand handle. The searchlight cannot be turned on until its covers are open below the plane.

The line of sight is restricted by stops from horizontal to 45-degrees dip. Rotation in azimuth is 20 degrees on either side.

10.10.2 Foxhole Periscope

The Signal Corps requested design and construction of a periscopic attachment to a 35-mm motion picture camera for photography of combat operations.[13a] The purpose was to set the camera and the top prism of the periscope about 18 in. above the operator's eye level on a rotatable stand, with the periscope used therefore as a viewfinder. A real field of 40 degrees diameter with magnification of 1× or 1.5× was requested. The exit pupil was to be larger than 4 mm.

Two alternative designs were submitted by Yerkes. Figure 41 shows Type 1. In this system simple lenses are used throughout, with the exception of the hyperchromat at the diaphragm. Each of the paired simple lenses is so shaped that the system is aplanatic, surface by surface. The accumulated longitudinal color is corrected at the pupil point by the zero power hyperchromat. The system has curved field but is fully free from astigmatism and coma. The spherical aberration is sufficiently small, owing to the shallow curves employed. The system has a real field of 40 degrees diameter, 10-mm exit pupil, and 2-in. eye relief.

Figure 42 shows Type 2. The erecting system in this instrument employs a symmetrical separated triplet hyperchromat. Because this triplet has positive power at the pupil, it is necessary to compensate the astigmatism thus introduced by negative astigmatism at the other two paired lenses. In this instrument the real field is 40 degrees, with 7-mm exit pupil and eye relief of 1.6 in. Only seven elements were used, which have smaller diameters than those in Type 1. The aberrations of Type 2 are somewhat larger than those of Type 1.

Both designs were submitted to the Signal Corps for development.

10.10.3 A 110-in. Periscope for the P-51 Airplane

A periscope 110 in. in length was designed at Yerkes to enable the pilot of a P-51 airplane to extend his view 12 degrees below horizontal.[13b] The lenses are approximately 8 in. in diameter and are to be made of plastic. The eye lens is to be fitted into the canopy of the airplane in such a way as to cause minimum disturbance when the pilot sweeps his vision from looking through the Plexiglas to looking through the eye lens of the periscope. Although several groups expressed considerable interest in this development, it was not covered by a Service request and time did not permit making a model.

From a schematic lay-out of the nose of the P-51b, it appeared that the pilot could normally see only about 3.5 degrees downwards below the fuselage reference plane. A periscope 84 in. long from entrance pupil to exit pupil would increase the clear downward vision to 13 degrees, and a periscope 115 in. long to about 25 degrees.

The proposed design made use of doublets of CHM and styrene. The length between lenses was 113 in., and between entrance and exit pupils 135 in. The real field was 24 degrees diameter with an exit pupil of 3 in., and eye relief of 11 in. The system employs ten elements with apertures from 7.3 to 7.8 in.

10.10.4 P-80 Periscope Design

In the spring of 1945 a request was received from the Air Forces for a periscopic viewing system for P-80 airplanes which were to be converted into photographic ships.[15] Such a periscope was to have a total real field of 45 degrees with an exit pupil 5 in. in diameter located at the eyes of the pilot. No part of the periscope was to interfere with any of the pilot's motions and all parts were to be within the plane. An unobstructed vertical view was desired.

Figure 43 shows a cross section of the optical

[redacted]

system proposed by the University of Rochester under Contract OEMsr-160. No details were worked out on the mounting, owing to uncertainty of the structure of the airplane. It is believed that such an installation must of necessity be accomplished at the factory by engineers with complete knowledge of the nature of the plane.

The negative magnification inherent in a system meeting the specifications is a great disadvantage to the pilot, although no doubt better than no viewing system at all. The only possible improvement would be to set aside ample space in the design of the airplane for a viewing screen of large size, installed on the instrument panel in line with the pilot's most convenient sight, on which is cast at least a unit-power image. In order to obtain sufficient field and illumination, a rather complicated periscope system with large lens elements would be required. Sufficient room forward of the instrument panel would have to be set aside for accommodation of the large periscope tube and large prisms or mirrors. Every effort should be made to avoid slight bendings of the optical axes in favor of use of right angle prisms or equivalent mirrors. Finally, such a system should be equipped for scanning from forward horizon to rear horizon by means of a head prism in a streamlined blister.

10.11 DISCUSSION

For the most part the instruments delivered to the Services were developments parallel to types already in production or under development by the several branches of the Services. The overlap in effort proved useful, however, in stimulating activity and in isolating factors that could be improved. Many of the NDRC ideas and improvements were incorporated either directly or indirectly in Service prototypes.

There can be no single group of detailed recommendations covering so broad a subject as summarized in this chapter. It is evident that many of the instruments were brought close to the limits of perfection possible with existing materials, and that the principles evolved in the work might readily be applied to incorporation of improved materials. The appearance of a glass capable of combining with ordinary glass types for reduction or elimination of secondary spectrum would remove a group of problems common to all visual systems involving image erection, tube extension, or, as in periscopic systems for submarines, small tube diameters and many elements. Fluorite represents only a par-

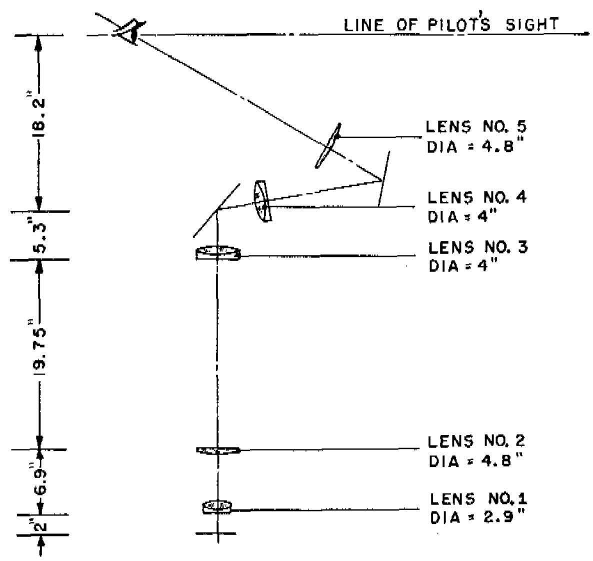


FIGURE 43. P-80 viewing periscope.

tial solution to date, and introduces almost as many difficulties as it removes.

It is probable that many of these visual instruments might profit by discriminating use of aspheric surfaces. Developments along such lines should certainly include sponsorship of glass-molding techniques of production character and accuracy.

Many of the instruments described in this chapter have an abundance of glass-air surfaces, and elements of high index. For these reasons it is probable that transmission has been impaired. Further work should always keep in mind as careful a balance between performance and transmission as possible, and actual models should incorporate the best possible surface coatings. In view of field experience that coated surfaces often achieve no permanent gain because of contamination in use, it would appear that all production optical systems should employ sealed optics.

[redacted]

10.12 RECOMMENDATIONS BY NDRC

1. A full study of all available designs for tank telescopes should be made. Present requirements demand not only a wide field and a 7-mm exit pupil, but also that the optical system fit inside the present 2-in. diameter tube which is now in use. If studies show that a satisfactory result cannot be achieved when the lenses are limited to 2 in. diameter, then consideration should be given to two possible modifications. Either the size of the tube should be increased slightly or the field or exit pupil should be reduced somewhat until a compromise is reached where definition over the whole field is adequate, as judged by field tests.

2. The development of the split-field tank and antitank telescopes should be continued and models should be field-tested to show whether these designs represent promising approaches to the problem raised by the need for both high and low magnification.

3. A *complete redesign is indicated for* submarine periscopes in order to reduce present aberrations, particularly in some models. Color and curvature of field now limit photographic resolution seriously. Fluorite could be used in both doublets of the erector system to reduce color to an insignificant level. Curvature of field can be compensated by using a special camera lens, such as has already been delivered for the 1.4-in. periscope, unless a new design for the periscope produces a field sufficiently flat to permit using the present camera lens. Rare-earth glass would help markedly in designing an improved periscope.

Chapter 11

PROJECTING SYSTEMS AND OTHER SPECIAL OPTICAL DEVELOPMENTS

By *Theodore Dunham, Jr.* and *James G. Baker*[a]

Two requirements for special projecting systems arose under Section 16.1 of NDRC. One of these was based on a Service request, while the other arose in connection with experimental work on the binocular testing program. These are described in this chapter, together with two special optical developments of different kinds.

11.1 WIDE-FIELD PROJECTOR FOR DOME TRAINER

Under Project NA-200, the Special Devices Division of the Bureau of Aeronautics requested that a projector be designed and constructed which would project on the inside of a dome, with a radius of 9 ft, moving images of aircraft for training purposes. A field of 180 degrees horizontally and 90 degrees vertically was desired, with a relative aperture of about $f/2$. This imposed very severe difficulties in the matter of optical design. Nevertheless, an optical system which appears to be entirely satisfactory was developed.

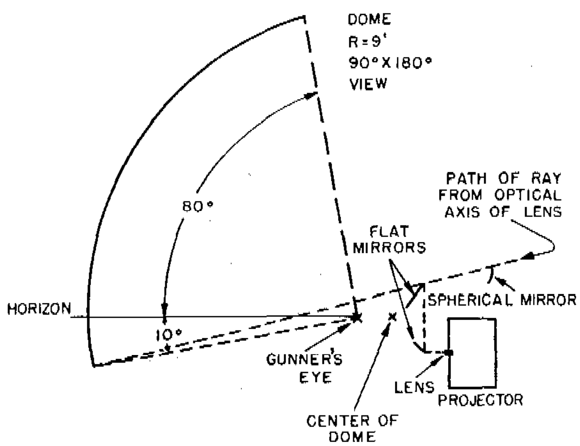


FIGURE 1. Optical layout for wide-field projector.

[a] Dr. Dunham is Chief of Section 16.1 NDRC and Dr. Baker is at the Harvard College Observatory. The first two sections of this chapter have been written by Dr. Dunham; the third section by Dr. Baker.

Figure 1 shows a layout of the optical system finally developed by the Yerkes Observatory[1] under Contract OEMsr-1078, based to a considerable extent on suggestions made by the Special Devices Division. An $f/2$ modified Petzval lens with a field of about 14 degrees is used in combination with half of a spherical mirror 12 in. in diameter, which increases the field by a factor of ten. The mirror has little effect on spherical aberration and coma, and no effect on chromatic aberrations. The curvature of field of the mirror is opposite in sign to that of the lens, and they are made to cancel one another

TABLE 1. Optical design of a wide-field projector for dome trainer.

Element	Radius (in.)	Thickness or separation (in.)	Glass	Remarks
Film	Flat	1.795	air	Adjust to focus image on dome
	—3.884			
1		0.237	DBC-1	1.625″ OD
	—1.765			
		0.007	air	
	+3.633			
2		0.236	DBC-1	1.625″ OD
	—5.138			
		0.158	air	
	—2.252			
3		0.105	EDF-1	1.625″ OD
	+24.37			
		1.891	air	
	—4.989			
4		0.135	EDF-1	2.08″ OD, Bevel to 1.70″ on rear
	+4.499			
5		0.503	BSC-2	
	—2.265			2.08″ OD
		0.007	air	
	+13.44			
6		0.285	BF-2	2.25″ OD
	—10.16			
		55.35	air	Path bent by plane mirrors
7	—9.265		Front surfaced mirror	
		144	Approximate distance to dome	

to a close approximation. The astigmatism of the lens is varied to counteract, as nearly as possible, that introduced by the mirror. A 6-element lens is capable of reducing higher order aberrations to the point required by the 330× magnification which is specified for this projector. There is considerable distortion, but this is not serious.

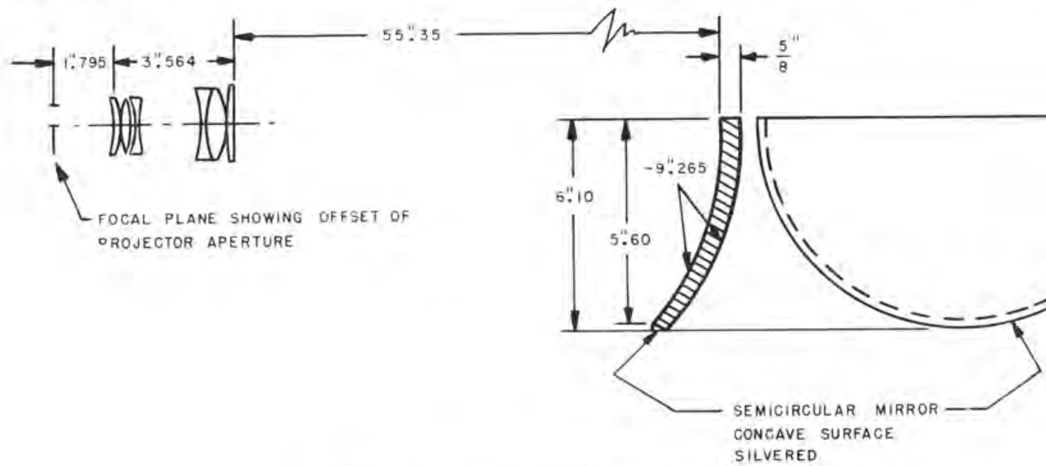


FIGURE 2. Optical design for wide-field projector.

The details of the optical design are shown in Figure 2 and in Table 1. In the final installation it is intended that the path should be bent by two reflections, as shown in Figure 1, so as to yield a compact system with the light path clearing both the projector and the head of the observer.

Figure 3 shows the projector set up temporarily for testing in a room, with the projected image of a coarse reticle. Illumination and resolution were adequate. It seems likely that this design will satisfactorily serve the purpose for which it was designed.

11.2 HIGH-RESOLUTION PROJECTION LENS

In connection with the binocular testing program at Dartmouth College (Contract OEMsr-1058), a projector of high optical performance was required for projecting on a screen images of small black targets with the absolute minimum of light directed into the images as a result of aberrations or of actual scattering by the glass surfaces of the lens elements. A narrow field was entirely acceptable, so that off-axis aberrations were unimportant. For this reason it was satisfactory to use a simple achromatic doublet, corrected as well as possible for spherical and chromatic aberration. The design was undertaken by the Yerkes Observatory under Contract OEMsr-1078.[1a]

In view of the fact that the images were to be observed at low levels of illumination (scotopic vision), it seemed desirable to adjust the

FIGURE 3. Reticle image projected on dome.

color correction to take account of the shift in effective sensitivity of the eye which occurs when passing from high to low levels of illumination. At 10^{-2} millilamberts, the maximum

absolute sensitivity of the eye[2] is at 5,060 A. The relative visual stimuli at low levels of illumination were computed, taking account of the energy distribution in a black body source at 3,000 K and of the rate of change of refractive index with wavelength. Figure 4 is a plot

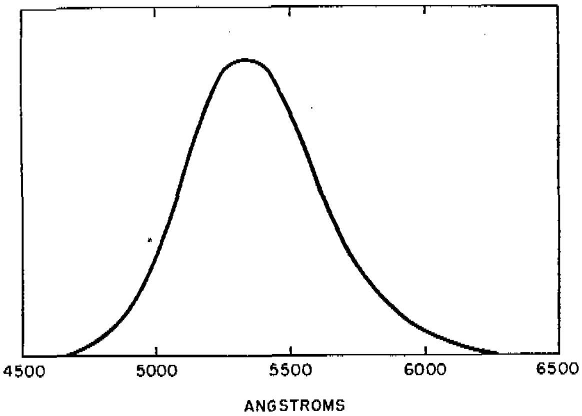


FIGURE 4. Relative visual stimuli at low levels of illumination.

showing the relative response of the eye per unit range of refractive index, as a function of wavelength. This curve shows that the maximum stimulus lies at 5,250 to 5,330 A, and that the curve is reasonably symmetrical. Hence, the minimum focal length of the doublet should be placed at about 5,330 A, with the focal lengths for F and D approximately equal. If the lens is achromatized for the mercury green line (5,461 A), then D and F will produce a response about 10 per cent as great as that produced by light having the wavelength of the green line.

The design for a lens corrected as well as possible for minimum wavelength at 5,461 A is

TABLE 2. Optical design of high-resolution projection lens.

Radius (in.)	Thickness (in.)	Glass	n_D	ν
+213 ± 10				
	0.325 ± 0.01	DF-1	1.6058	38.1
+ 9.34 ± 0.03				
	0.525 ± 0.01	LBC-2	1.5727	57.3
− 16.85 ± 0.10				

shown in Table 2. The design takes account of the finite distance of the image, which in this case is 1,100 in. The source is located 30.5 in. from the surface of the flint element. The lens has a relative aperture of $f/9$. The aberrations of this lens, for an axial image, are shown in Figure 5.

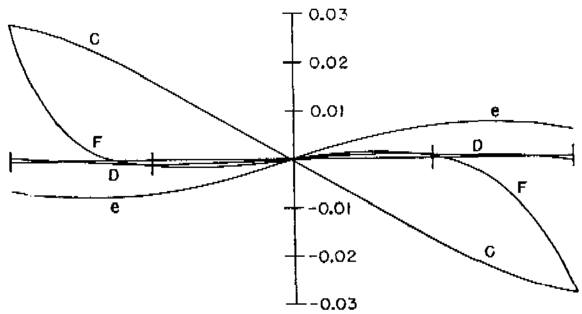


FIGURE 5. Angular ray aberrations for projection lens, in mils. (Each interval on abscissa represents one-quarter aperture of the lens.)

A lens was designed at a later date for use as a precision collimator at the Massachusetts Institute of Technology [MIT] (Contract OEMsr-203), which was to deliver parallel light. It was found that the only change required was to increase the radius of curvature of the first surface from 213 to 278 in. in the design of the projector lens shown in Table 2.

Models of these lenses were made at the Ray Control Company in Pasadena. Some were refigured at Harvard (Contract OEMsr-474) and were carefully cemented in cells to avoid strain. Tests showed their performance to be excellent. These designs are likely to be of interest for other applications.

11.3 SPECIAL OPTICAL DEVELOPMENTS

11.3.1 A Plastic Condenser Lens

Under Contract OEMsr-474 in the summer of 1943 an $f/1.5$ condenser lens of plastic and of 8 in. clear aperture was completed.[3] The glass condensing lens already in use in the field was much too heavy for general use and also gave too large a circle of confusion for the photoelectric application involved. The circle of confusion for all light from the condenser was to have a diameter of 3 mm.

A 2-element condenser of Lucite was made up in accordance with the following table.

TABLE 3. Design data for an 8-in. $f/1.5$ condenser.

Surface	Radii (in.)	Separations (in.)	Material
1	11	1.1	Lucite
2	plano	0.0	
3	6	1.0	Lucite
4	11		

The form of condenser lens chosen was not color corrected but had very much reduced spherical aberration as a result of the division of the convergence between two lenses. The color residual proved small enough for the purpose. The weight of the final plastic lens system mounted in sheet metal was less than 5 lb. The system is to be recommended for general use where light weight and a 3-mm circle of confusion are to be used. In production, such a condenser system should be made of molded plastic lenses.

11.3.2 A Cemented Triplet Coronagraphic Objective

At the request of the Navy, NDRC undertook to provide under Contract OEMsr-474 (Harvard) a cemented triplet coronagraphic objective.[3a] Most of the work was completed during 1945 and delivery was made to the Navy late in the year.

The *coronagraph* is a simple type of telescope designed for the purpose of producing an artificial eclipse of the sun. The light from the sun is focused by means of a simple objective lens onto an opaque disk just slightly larger than the image of the sun. In this way practically all of the sunlight is eliminated from the remainder of the optical system. The light from the solar corona, the object of study, is collected again by a field lens immediately behind the opaque disk and directed toward a projection lens system which refocuses the corona onto a photographic film. Generally a color filter, or more recently, a quartz monochromator filter (see Chapter 9) is used for the purpose of restricting the color range of the scattered light within the atmosphere and the instrument. The light from the corona is in part made up of monochromatic radiations. Consequently, by the use of filters, the image of the corona in these special wavelengths can be greatly increased in contrast, relative to the general background of sunlight.

By far the most sensitive part of the system is the objective lens. The coronal light is only perhaps a millionth as bright as the sunlight over the visual range of spectrum, and much of this light comes from a continuous spectrum.

The slightest defect in the coronagraphic objective lens will scatter more stray light around the occulting disk than comes from the corona directly. A bubble only 0.1 mm in diameter cannot be tolerated. Seeds, bubbles, striation, sleeks, scratches, etc., must all be eliminated by provision of a nearly perfect lens. The light diffracted from the edge of the objective around the occulting disk is trapped farther down the tube by making the clear aperture of the following projection system smaller than the image of the objective focused on the projection lens by the field lens. Within this focused image of the objective it is also possible to eliminate any fixed spots like minute bubbles. In general, however, it is almost an absolute necessity that the objective lens be nearly perfect.

Spectrographic use requires that the light coming around the edge of the occulting disk be focused onto a slit tangential to the image of the disk. The spectrograph serves as its own filter, but requires that the image of the corona in the several colors be in sharp focus on the slit face. With a simple objective lens not only is the corona image in widely separated colors out of focus but also the out-of-focus light of the sun in colors other than that for which the size and position of the occulting disk are determined, spills onto the slit. This additional illumination of the grating within the spectrograph will cause considerable scattered light and reduction of the exposure time below what is needed to obtain the coronal lines.

Owing to the importance of the Navy program making use of solar observations, it was thought necessary to attempt a nearly perfect cemented triplet objective. For this purpose an ordinary doublet of crown and flint would have been impractical. The coronagraphic lens is cleaned rather frequently. A flint-glass surface

would not be able to withstand such cleanings for long under the critical conditions of use.

The triplet coronagraphic objective form was used in order to have the hardest type of optical glass on the outside. The design adopted was that of the ordinary cemented doublet with nearly equiconvex first element. The rear element was scarcely more than a cover plate, although allowance was made in the design for its presence. The design is given in Table 4.

The system is well corrected for spherical aberration and color but not for coma. The required field of view is so slight that coma is of no importance.

The lenses were made of glass selected for freedom from all detectable defects. Fine grinding was carried to unusual length in order to remove any vestiges of subsurface defects that would ultimately impair the performance. The assembled lens system gave a sharp clear image. At the time of delivery, the meticulous cementing task had not been carried out and was expected to be accomplished later under Navy direction. The three lenses individually were free from detectable defects when illuminated in a dark room by means of a narrow beam of light from a 250-w sealed beam reflector.

TABLE 4. Optical design of the coronagraphic triplet objective, $f = 9.6$ in.

Surface	Radii (in.)	Separations (in.)	Indices	Glass types
1	44.19	0.89	1.517	BSC-2
2	—41.04	0.77	1.617	DF-2
3	—496.0	0.89	1.517	BSC-2
4	—556.2			

[redacted]

Chapter 12

REFLEX SIGHTS

By *John W. Evans*[a]

FIVE ORGANIZATIONS under contract with OSRD did extensive work in the development of reflex sights. They are the Yerkes Observatory of the University of Chicago [Yerkes], the Mount Wilson Observatory of the Carnegie Institution of Washington [MWO], the Institute of Optics of the University of Rochester [Rochester] and the Polaroid Corporation [Polaroid] under contract with Division 16, NDRC, and the Eastman Kodak Company [Eastman] under contract with Division 7, NDRC. The work consisted in the design of optical systems, and the construction of sample sights for optical and service tests. Several new types, such as the Lens Mangin, Bowen, Fly's Eye and solid sights, were devised and successfully demonstrated, while others were investigated theoretically and rejected as unsatisfactory.

12.1 CHARACTERISTICS OF REFLEX SIGHTS

12.1.1 Introduction

The advent of military aviation and aerial gunnery brought peculiar sighting problems which were not satisfactorily met by any existing forms of iron sights or telescope sights. A good aircraft sight must fulfill the following requirements:

1. The gunner must be able to see his aiming pattern superimposed on the target *at infinity* to obviate the necessity for accommodation in sighting.

2. The gunner should have as much *eye freedom* as possible, i.e., the position of his eye should not be rigidly restricted as it would be, for example, if he were using a telescope sight. The process of bringing the sight to bear on the target involves a certain amount of delicate manipulation which is usually already hampered by considerable acceleration in almost any direction. The necessity for holding the eye in a fixed position during the operation is obviously a serious handicap.

3. The pattern seen by the gunner should provide some aid to deflection shooting. In other words, there must be some means of estimating or setting the correct lead for a target moving across the line of sight at high speed.

4. The sight must obscure as little of the gunner's field of vision as possible.

5. The sight must not interfere with other instruments on the panel. This usually imposes serious limitations on its size.

The reflex sight was devised to meet these requirements. The first model developed by the Army Air Forces was the N-1, designed in 1933. Since that time the reflex sights used by the U. S. Army and Navy have undergone a series of improvements and modifications for specific purposes. At the outbreak of World War II NDRC undertook to develop further certain types of reflex sights. At the same time the Army and Navy expanded their activities in developing reflex sights, and several commercial firms initiated development programs.

While the present report is concerned solely with the activity of OSRD, the reader should not have the impression that it was the only reflex sight work done during World War II, since the programs of other agencies were equally important.

At present the reflex sight is used almost universally for aiming the guns of all types of military aircraft, and is being introduced on certain types of antiaircraft guns. At the time of the termination of OSRD contracts the development of a reflex sight for the infantryman's rifle was in progress. It is perhaps not too much to say that a properly designed reflex sight is the best optical device for aiming any weapon for which a telescope sight is unsuitable, and it appears probable that ultimately

[a] Harvard University. Formerly with University of Rochester.

these two will be the only sights used for military purposes.

12.1.2 General Description of the Reflex Sight

The elements of a conventional reflex sight are shown in Figure 1. They consist of an il-

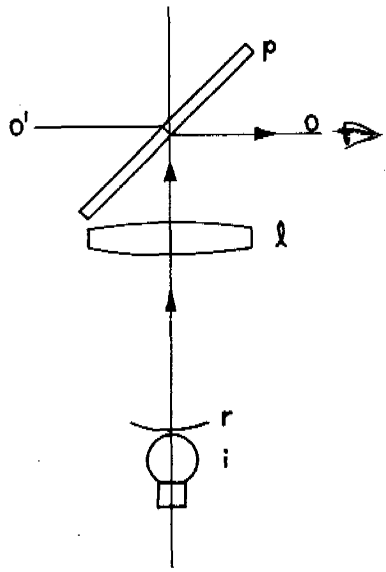


FIGURE 1. Elements of a reflex sight.

luminator i, a reticle r, a collimating lens l, and a reflex mirror p.

Light from the illuminator passes through the reticle to the lens, which collimates it, and thence to the reflex mirror, which projects the image of the reticle at infinity in the direction OO'. The reflex mirror, which is usually a plane-parallel plate glass, reflects a fraction of the light and transmits most of the remainder. Thus, on looking through the reflex mirror in the direction OO', the observer sees the bright image of the reticle pattern at infinity.

A typical reticle pattern for a gunsight consists of a central dot, the *aiming point*, surrounded by a series of concentric circles and, in some instances, radial lines. The sight is aligned with the gun, or *boresighted* so that the aiming point coincides with the line of fire at a given range. In shooting at a rapidly moving target, the problem is to aim ahead of it, by the appropriate deflection, to insure that it crosses the line of fire at the instant the projectiles reach the target's range. This is accomplished by leading the target with the aid of the circles of the reticle pattern. Each circle indicates the appropriate lead for a given velocity across the line of sight, and hence is referred to as a *speed ring*. The apparent radii of the speed rings are commonly multiples of 70 mils, which is the lead for a velocity of 100 mph across the line of sight for a mean bullet velocity of 2,100 fps.

The method of aiming is shown in Figure 2,

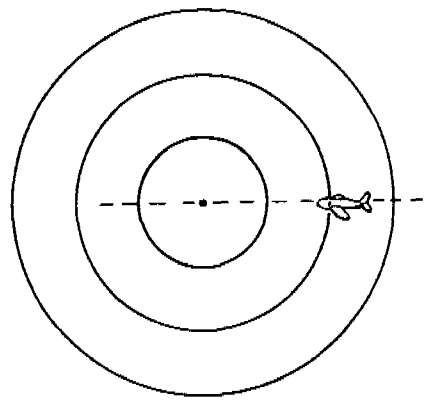


FIGURE 2. The gunner's view of speed rings and target.

which depicts the gunner's view through the sight. The dotted line indicates the path of a target relative to the gun, with a component of velocity across the line of sight of 200 mph. The gun is aimed by placing the 200-mile speed ring on the target in such a position that the projected velocity passes through the aiming point. The gun is then swung to follow with the target in this position on the reticle pattern and is fired as long as the aim can be maintained or until the target disintegrates.

Recently, lead-computing mechanisms have been introduced which automatically deflect the sight with respect to the gun. The gunner merely keeps the aiming point of his sight on the target. Reflex sights for this use do not require speed rings.

12.1.3 Characteristics of Reflex Sights

The arrangement of optical parts in a reflex sight can be varied in many ways, but its func-

[redacted]

tion is always the same—to project a collimated image of a reticle pattern in the direction of the point of aim. For example, Figure 3 shows

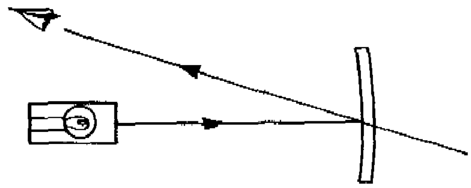


FIGURE 3. An unconventional type of reflex sight.

a variation in which a partially reflecting mirror serves both as collimator and reflex plate. Regardless of its form, there are certain features of any reflex sight which determine its usefulness for a given purpose, and furnish a basis for comparison with other sights. They can be enumerated as follows:

1. Brightness and uniformity of the projected image.
2. Eye freedom.
3. Apparent radius of reticle pattern.
4. Parallax on and off axis.
5. Chromatic blurring of the pattern.
6. Transmission in the direction OO'.
7. Reliability and ease of repair in case of failure.
8. Size (interference with other equipment).
9. Obstruction of the observer's field of view.
10. Power consumption and heat dissipation.

A discussion of each of these characteristics follows.

Brightness and Uniformity of Projected Image

The brightness of the projected image determines the visibility of the reticle pattern against the target area. Let B_0 be the brightness of the target area, and B_1 the brightness of the reticle pattern which would be seen by looking directly into the collimator lens of the sight without any reflex mirror. Let ρ be the fraction of light reflected and τ, the fraction transmitted by the reflex mirror. To an observer using the assembled sight, the target area appears with brightness of $B_0\tau$ and the reticle pattern with brightness $B_0\tau + B_1\rho$. The visibility of the pattern can be expressed then as the fraction:

$$V = \frac{B_0\tau + B_1\rho}{B_0\tau} = 1 + \frac{B_1\rho}{B_0\tau}.$$

Although the eye is quite sensitive to small discontinuities in brightness and can readily detect differences of 5 per cent, the minimum value of V at daylight levels of illumination which will permit a pattern of narrow lines of the order of 1 mil wide, or small dots, to be instantly visible without a short search is probably about 1.2 to 1.3. As the illumination of the landscape decreases, the minimum usable value of V increases. In the light of the full moon, for instance, V should be at least 3.0 for targets against the sky with 1-mil lines.

The necessary brightness of the reticle pattern is fixed, then, by the brightest target area against which it is to be projected. An antiaircraft sight must be usable against the brilliant translucence of a hazy sky in the neighborhood of the sun, which may attain a brightness of thousands of lamberts. A sight for use on ground targets, on the other hand, generally requires much less light since ground areas rarely exceed 5 lamberts in brightness. However, sky line targets with background brightnesses of 30 or 40 lamberts may be encountered, and such targets must not infrequently be viewed against the much brighter sky near the sun. If *all* contingencies are to be anticipated, the sight for ground targets should meet the same brightness requirements as the antiaircraft sight. In many instances it is sufficient to provide a dense neutral filter which can be flipped into position between the reflex mirror and the target to reduce the apparent brightness of the target area so that a less brilliant reticle pattern can be used.

Unfortunately, no quantitative data are available on the reticle brightnesses of most of the sights which have been developed under OSRD, although satisfactory estimates of visibility can be made for the daylight illuminated sights.

A second important characteristic of the projected reticle image is the uniformity of its brightness. Unless due care is taken in designing the illuminator, particularly in a wide-angle sight, different parts of the reticle image are apt to show differences in brightness. Usually the center of the pattern appears brightest. One also frequently finds that the brightness of the whole pattern varies as the observer's eye moves around in the eye space. It is not difficult to

[redacted]

avoid either of these faults singly, but the simultaneous elimination of both, combined with the achievement of great reticle brightness, requires the even and powerful illumination of both reticle and the exit pupil. In large-aperture wide-angle sights illuminated by electricity this becomes a major problem.

The reason for the difficulty lies in the peculiar inefficiency of the reflex sight in utilizing the available light. Fortunately it is not difficult to use a condenser which directs most of the light of the lamp onto the reticle. However, only a small fraction of the light which falls on the reticle passes through the narrow openings of the pattern. Unless a carefully designed condenser is used, a large part of the light which does get through the reticle openings is generally outside the solid angle containing the collimating lens, and so is wasted. Finally, a bare-glass reflex mirror is usually employed which reflects only about 9 per cent of the light emerging from the lens.

The ideal illuminator would be one which concentrates most of the light of the lamp on the openings of the reticle pattern in a solid angle which just fills the exit pupil. Such a device could doubtless be designed, but it would be expensive and bulky. Since plenty of power is usually available, it has seemed more practical to use simple illuminators, and make up for the losses by using lamps of relatively high wattage in most of the OSRD sights. Acceptable reticle brightnesses are attained, and the visibility of the pattern against unusually bright target areas can be enhanced to any desired extent with the aid of a neutral absorbing filter mounted so it can be moved into position just beyond the reflex mirror. This has the effect of reducing τ without affecting ρ.

The brightness of the projected reticle pattern is completely independent of the focal ratio of the collimating lens. However, unless the illuminator is designed to just fill the lens it will be easier to illuminate a sight with a high aperture ratio than one with a small ratio, since the latter has the larger reticle area to be illuminated.

One of the most interesting developments in the OSRD reflex-sight projects is the use of daylight for illumination. Its prime advantage is that the visibility of the reticle pattern can be made approximately independent of the brightness of the target area. Hence, the pattern remains conspicuous against the most brilliant sections of the sky. Attendant advantages are the simplicity of the optical system and the reliability of the illumination. Against the advantages, there is the disadvantage that the reflex mirror must be coated with a partially reflecting film to raise ρ to the neighborhood of 0.5. This means either a complicated sandwich-type mirror with the film protected by a covering glass or a toughened film on an external surface of a one-piece plate. Even the toughest films are not quite as durable as bare glass. Since it is doubtful whether even diamond would withstand repeated G.I. cleanings without some evidence, the external films present a problem.

If the sight is to be used at night as well as by day, it is necessary to provide an auxiliary electrical illuminator. But since the target area at night is hundreds of thousands of times fainter than in daylight the achievement of sufficient reticle brightness is no problem, and an extremely simple (but carefully designed) illuminator is adequate. For the utmost efficiency in night use, it would also be desirable to have a bare-glass reflex mirror readily interchangeable with the coated mirror used in daylight.

One of the several possible types of daylight illuminated sights is shown in Figure 4. Its great simplicity is apparent at once. The reticle is illuminated by the target area itself. The apparent brightness of the reticle B_t equals kB_0, where k is the transmission of the sight without the reflex mirror for light which enters through the reticle. The visibility is then:

$$V = k\frac{\rho}{\tau} + 1.$$

It is independent of the brightness of the target area. Typical values of k, ρ, and τ are respectively 0.65, 0.4, and 0.6, and V equals 1.43.

Eye Freedom

Eye freedom is one of the most prominent of the advantages of the reflex sight. There is a region referred to as *eye space* behind the re-

flex mirror from every point of which the entire reticle can be seen. The datum of practical interest is the diameter of the cross section of the eye space perpendicular to the line of sight at the observer's normal eye distance. The limiting ray from the edge of the reticle through the near edge of the lens in the same meridian plane is the boundary of the eye space. Figure 5 shows the limiting rays and the geometry of the eye space. The lettered parts and distances are as follows:

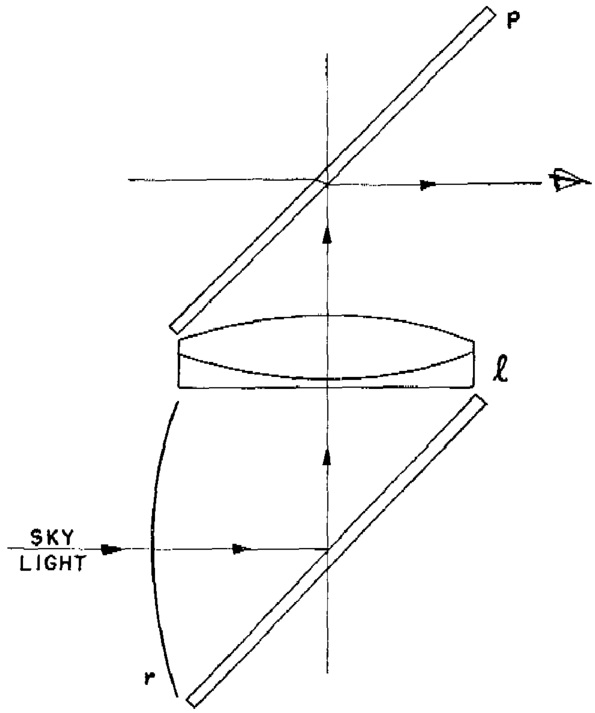


FIGURE 4. Daylight illuminated sight.

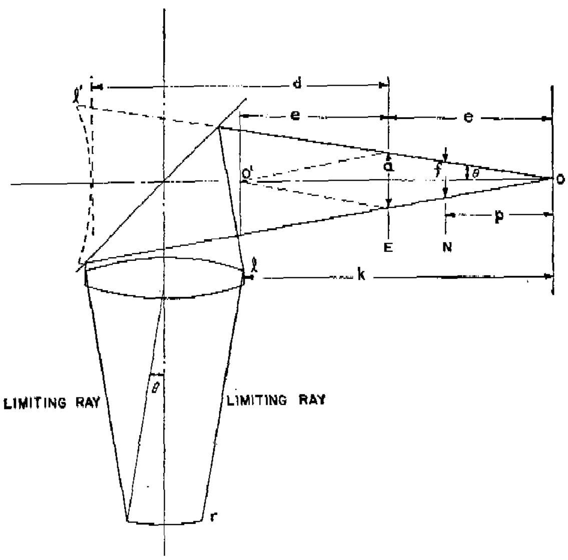


FIGURE 5. Geometry of eye space.

- r reticle (of angular radius θ)
- l lens
- l' image of lens reflected in first surface of reflex mirror
- E plane of exit pupil
- O eye point at greatest eye relief
- N plane of normal eye position
- d distance l' to E
- e distance E to O
- k distance from edge of sight to O
- A aperture of lens l
- a aperture of exit pupil
- f diameter of circle of eye freedom
- p distance N to O

The exit pupil of a reflex sight nearly always coincides with the lens aperture. However, since the Mount Wilson group has made some notable exceptions to this rule, the more general case is considered.

The greatest eye relief is simply the distance at which the exit pupil appears filled by the reticle pattern with an apparent radius of θ. Hence,

$$e = \frac{a}{2} \cot \theta.$$

The eye space consists of a pair of cones based on the exit pupil with apices at O and O', both of which are at a distance e from the E plane. It is represented in Figure 5 by the shaded area. The only part of the eye space of practical interest is that portion which lies beyond the edge of the sight where it can be reached by the observer's eye. It is completely specified by the distance k, the angle θ and, if the exit pupil is between the edge of the sight and O, as is rarely the case, the distance e. If the normal eye distance is known, the eye freedom, f, can be calculated from the relation:

$$f = 2p \tan \theta.$$

The foregoing calculations are based on the assumption that the sight is circularly symmetrical. If the reticle or collimating lens are noncircular, the calculation would have to be carried out for the various meridian planes of

interest. Usually it is sufficient to know the vertical and horizontal eye freedom.

Apparent Radius of Reticle Pattern

The apparent radius of the reticle pattern is an important specification of a sight. It depends, however, on the off-axis correction of the lens and the capacity of the illuminator to fill a large reticle uniformly, and hence is not an independent characteristic of the sight which can be adjusted at will merely by making a reticle of the appropriate size.

Parallax

The parallax of a sight determines the accuracy of aim. If a sight has the mythical perfectly corrected lens, the projected reticle pattern appears to remain perfectly stationary against a distant background as the eye is moved from one side of the lens aperture to the other. If, however, it has an imperfectly corrected lens, the pattern appears to shift against the distant background, and the aim will be different for different positions of the eye. The extreme apparent shift (usually measured in mils) as the eye moves across the diameter of the lens has been termed the *parallactic range,* denoted by P, by the Yerkes Observatory workers. We shall retain the notation here.

Generally, P varies from center to edge of the reticle pattern. At the center it is due to spherical aberration alone, while off the axis coma and astigmatism become effective. Curvature of field is effectively compensated by use of a curved reticle, and in instances where the reticle pattern consists entirely of concentric circles or radial lines the parallactic shift due to astigmatism can be well corrected by curving it to the primary or secondary focal surface.[1]

The tolerances in P usually requested by the Armed Forces can be expressed roughly by the formula,

$$P = 2 + 0.015\theta$$

where θ is the angle off axis expressed in mils. The reason for the larger tolerance off axis is that the accidental error of the gunner's estimate of deflection increases with the deflection. While it is certainly desirable to hold the systematic errors due to imperfection in the sight to a minimum, a systematic error of 2 mils (deviation from the mean direction) in the 300-mile speed ring has little practical effect when the accidental error is probably not less than 15 mils.

Chromatic Blur

Chromatic blurring of the reticle pattern occurs when the collimating lens is imperfectly corrected for color. An off-axis point in the reticle appears as a short radial colored line, and a tangential line is broadened out into a colored band. The result is that the position of the dot or line is indeterminate. The simplest and most effective preventative for this defect is a collimating lens well corrected for color, although the use of color filters is very helpful if the illuminator can stand the additional strain. Tolerances for chromatic blur between the C and F lines should not be greater than those for parallax.

Transmission of Reflex Mirror

The transmission of the reflex mirror deserves consideration in instances where it occupies only a small part of the observer's field of view. It is undesirable to have a violent discontinuity in the brightness of the landscape at the edge of a reflex mirror. It has been observed that a loss of 50 per cent is very rarely noticed by military personnel, and it is likely that there would be no objection to transmissions as low as 20 per cent unless attention were specifically called to the fact that it is only 20 per cent.

If a sight is to be used at night, any loss in transmission is, of course, objectionable. Tests at the University of Rochester of visibility of objects against the night sky indicate that the range at which a target could be seen is about 20 per cent less when seen through a 50 per cent transmitting plate than with the unimpeded eye.

The reason for mentioning low transmission here is that it is the unavoidable concomitant of high reflecting power in a reflex mirror, and any use of partially reflecting films on the mirror to increase the visibility of the reticle pat-

tern by increasing ρ results in a decrease in τ, since $\rho + \tau$ cannot exceed 1.0.

Reliability

The reliability of a sight needs little comment. Perhaps the two most common sources of failure of reflex sights are the electric lamps and the reflex mirrors. It is wise to provide for quick and one-handed replacement of either of these parts.

Size

For most military purposes the sight should be as compact and as light as possible. This is particularly true of sights for use in aircraft where the user is figuratively slid into place with the aid of a shoehorn. The military requirements in size will not be completely satisfied until a sight of negative volume is devised.

One of the most promising means for reducing the overall size of the sight in fighter planes, and thus diminishing interference with other instruments and the pilot's field of view, is to eliminate the reflex mirror and to reflect the collimated beam from the armor glass. This requires a close tolerance on the parallelism of the two surfaces of the armor glass, but experience has already shown that this can be achieved. Instrument panels should be designed in the future to take account of the specific sight whether the armor glass is used or not. This is a requirement that, for some strange reason, has been almost universally disregarded in the past.

Obstruction of Field of View

Large obstructions in the observer's field of view are usually very objectionable because they can hide a target and delay its discovery. As far as possible the body of the sight is placed outside the normal field of vision and only an unframed reflex mirror is allowed to project.

Power Consumption

The power consumed in the illuminator of a sight is not ordinarily of any importance in itself. However, since the heat losses are roughly proportional to the power input, an observer who works in very close quarters will be interested in an efficient cool illuminator of low power consumption. A 100-w lamp can, under some circumstances, be a most uncomfortable neighbor. In extreme cases it may be necessary to provide a cooling system to remove unwanted heat.

12.2 TYPES OF OPTICAL SYSTEMS FOR REFLEX SIGHTS

Several distinct types of optical systems for reflex sights have been investigated under OSRD to meet the various requirements of eye relief, bulk, and accuracy. They are described briefly below with as little reference as possible to the specific sights of each type.

12.2.1 Lens Sights

The majority of reflex sights are of the "conventional" type shown in Figure 1, with a lens for a collimator, and it may be seen in the table in Appendix I to this chapter that the lens collimators outnumber all other types combined developed by OSRD. Their functioning is perfectly straightforward and requires no description. The problem of design is similar to that for a camera lens, but is simplified by the fact that the field can be given any desired curve.

12.2.2 Lens-Mangin Sights

The Lens-Mangin[1a] sight has an ingenious optical system originated at the Yerkes Observatory for use where very large exit pupils are necessary. The main work of collimating the light is performed by a spherical mirror, some of the aberrations of which are corrected by refracting surfaces.

The system is shown in Figure 6. Light from the reticle *r* is reflected by a partially reflecting dividing plate *d* to the Mangin mirror *m*, which has a lens surface on the front and a reflecting surface of silver or aluminum on the back. After reflection from *m* the light passes through *d* to a weak lens *l* and the reflex mirror *p*. This optical system differs from the simple Mangin,

which is well corrected for color and spherical aberration, in the presence of the lens *l*, which controls the coma. The result is an excellent

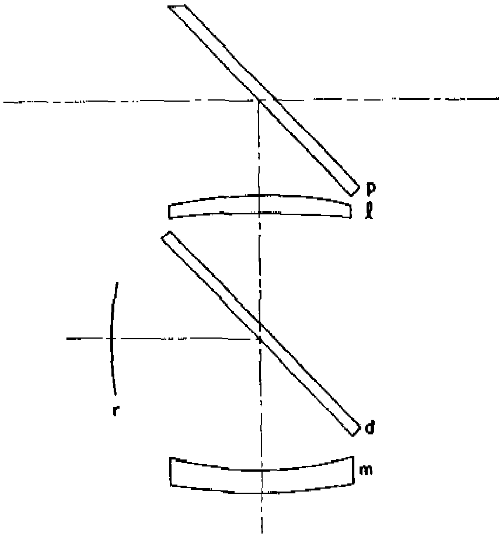


FIGURE 6. Lens-Mangin sight.

system with $P = 1$ mil for rings with radii up to 100 mils in focal ratios as high as 1.3.

The principal disadvantage of the Lens-Mangin type of sight is the loss of at least 75 per cent of the light in the dividing plate. However, it was found possible to obtain satisfactory visibility with moderate power input.

12.2.3 Solid Sights

For applications where large eye relief is unimportant (infantryman's rifle, antiaircraft guns, flexible aircraft guns, etc.) sights can be made relatively small and in some instances it was found that there were both optical and mechanical advantages in making the sight a solid block of glass or plastic. With one exception, all of the OSRD solid sights have the same general form as that shown in Figure 7. It consists of three pieces, two of which are cemented together with a half-reflecting film between them to form the reflex mirror *d*, and the third of which is simply a first-surface spherical mirror *m* which bears the main burden of collimation. The lens surface *l* immediately in front of the mirror corrects the spherical aberration, and the collimator is essentially a Mangin system with an air lens. In the assembled sight, light proceeds from reticle *r*, through the dividing surface *d* to mirror *m*. The collimated beam returns from *m* to the observer's eye by reflection from *d*. The surfaces *h* and *k* must, of course, be plane.

Another form of solid sight consists simply of a block of glass with a reticle at one end, and a lens surface and one separate lens element at the other. The only example of this type designed under OSRD is the solid "Figure-4" sight shown in Figure 14B.

The most conspicuous optical feature of the solid sight is the fact that its equivalent focal length in air is smaller by a factor of n (index of refraction) than the focal length in glass. This means that the field angles in glass are multiplied by n when the light emerges into air. The reticle of the solid system is thus

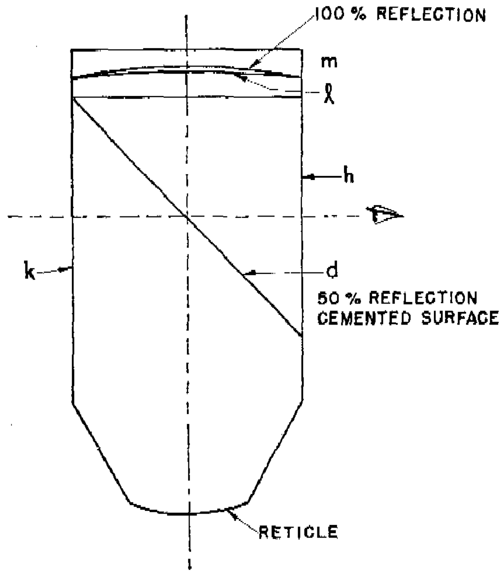


FIGURE 7. Solid Mangin sight.

smaller than that of an air system of the same length and field, and the off-axis aberrations are smaller. This advantage is accompanied, however, by the unavoidable introduction of some lateral color.

The mechanical advantage of the solid system is obvious. The parts are held accurately in position without the necessity of a complicated mounting and in small sizes the resulting unit is very simple to make and very rugged. Ex-

perience indicates, however, that the cemented diagonal in the Mangin form is a weak point which must be protected in mounting.

In some instances the smaller reticle permits a very decided gain in compactness when the optical system is to be folded as it is in the "Figure-4" sight.

The solid Mangin sights suffer from the same large loss of light as the Lens-Mangin type at the dividing surface, and since most of them have been designed for daylight illumination this is serious. An ingenious device for reducing this loss has been proposed by the Mount Wilson workers. If the dividing surface consists of a series of alternating layers of dielectric material of high and low indices such as zinc sulfide and cryolite, and if the refractive index of the glass is properly chosen, the light is reflected at the Brewster angle, and the reflected light is highly polarized while the transmitted light is polarized at right angles to it. If now a quarter-wave plate is inserted between the dividing surface and the mirror, the plane of polarization of the collimated beam is rotated 90 degrees with respect to that of the light reflected by the dividing surface, and is transmitted by that surface with no appreciable loss. Thus, it is theoretically possible to increase the product of transmission and reflection of the dividing surface from 0.25 to 0.50, doubling the brightness of the projected image. If the polarization is not complete the product will be somewhere between these limits. Dividing surfaces of the required type have been developed at the University of Rochester, but have not yet been tried in the solid Mangin sights.

12.2.4 Double Mangin Sights

It was suggested by the Mount Wilson group that a combination of two Mangin mirrors with a family resemblance to the Cassagrain telescope might constitute a useful collimator for a reflex sight in which a large exit pupil is desired. The reticle is placed in a hole in the center of the large primary mirror. The secondary obscures both the direct view of the reticle and the inner zones of the primary. To avoid the large blind spot the eye is raised well above the axis, and the exit pupil is lune shaped. Only half of the primary mirror is used. A preliminary investigation of the aberrations at the Yerkes Observatory indicates that for a focal ratio of $f/1$ the axial aberrations are small, but color is poorly corrected and the field aberrations are large. However the system is extremely compact. With a focal length of 10 in. the sight has approximate overall dimensions of 10x5x4 in. (excluding the reflex mirror) with an exit pupil about 8x2.5 in. The combined effects of aberrations and vignetting are such that a field of about 75 mils radius is the maximum usable.

It is regrettable that the details of the performance of the double Mangin system have not been investigated. On the whole it appears to be a promising sight for certain applications. For instance, it might be excellent as a lead-computing sight in a fighter airplane if mounted to use the armor glass as a reflex mirror, with the deflection set in by tilting the whole sight.

12.2.5 Schmidt Sights

The Schmidt optical system shown in Figure 8 has tempting optical properties for use in re-

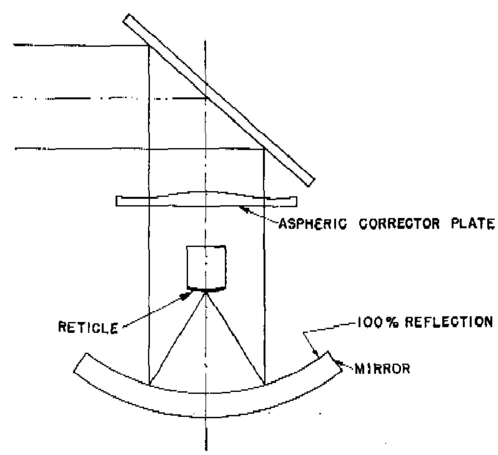


FIGURE 8. Straight Schmidt sight.

flex sights. It was found that the off-axis aberrations of a system with a focal ratio of $f/0.7$ are satisfactorily small. For a field of 100 mils radius, $P = 1.3$ mils, and both radial lines and speed rings can be used.

However the high focal ratio is not a fair indication of the compactness of the system, since the overall length is slightly more than twice the focal length. Also, the reticle obscures the center of the exit pupil, creating a large blind spot. The aspheric correction plate is not the serious drawback it would have been before World War II since methods have been developed for molding Schmidt plates of the requisite quality at the University of Rochester and many thousands of plates have been produced commercially at a very low cost.

The disadvantages of the unmodified Schmidt system appear to outweigh the advantages, and no efforts to develop a reflex sight from it have been made.

However the Bowen sight[2a] is a beautiful adaptation of the Schmidt optical principle designed for use in fighter airplanes with a very large exit pupil and a minimum of obstruction to the gunner's view of the instrument panel or the field outside the airplane. Its distinctive feature is the formation of a definite exit pupil at the normal eye position of the pilot, which limits the effective aperture to such an extent that the usual aspheric element of the Schmidt system can be dispensed with. A diagram of the main elements of the optical system is shown in Figure 9. Its simplicity is apparent.

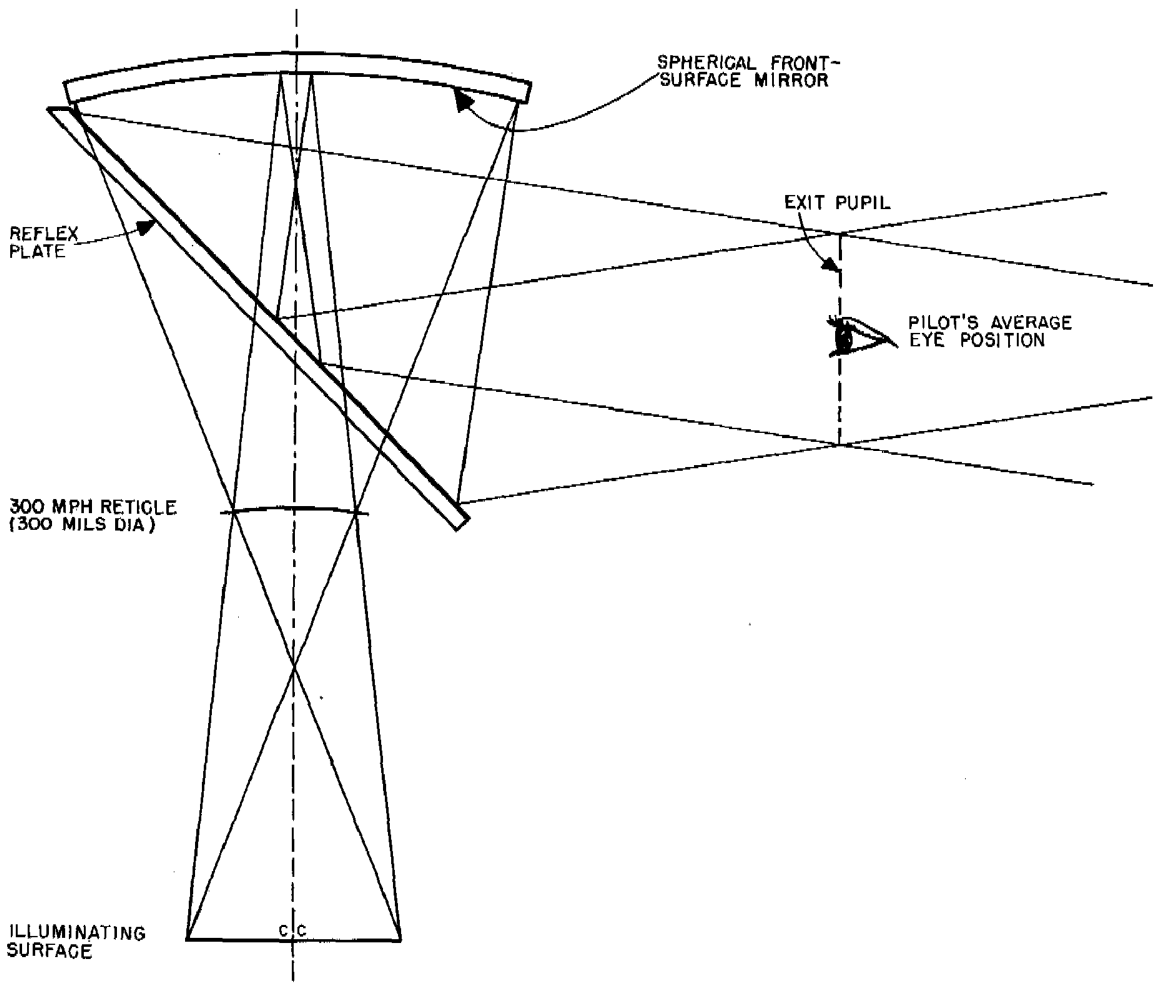


FIGURE 9. Bowen sight.

The collimator consists of a large spherical mirror. An illuminating surface is placed at the center of curvature [CC] of the mirror and its image reflected by the reflex mirror is the exit pupil. The spherically curved reticle is placed

in the focal surface of the collimating mirror (very nearly halfway between the mirror and CC). Mirror and reticle are concentric. Since the axis of the cone of light emerging from any point in the reticle is a radius of the mirror, the system has no optical axis in the normal sense, and hence no coma or astigmatism. The parallactic range is therefore the same over the whole field, and the reticle size is limited only by mechanical conditions.

Since the spherical aberration of the collimating mirror is not corrected, and is approximately proportional to the cube of the aperture ratio, the diameter of the exit pupil is limited. The parallactic range is about 1 mil at $f/2$, the aperture ratio adopted for the samples of the sight which were constructed.

12.2.6 Fly's-Eye Sight

The advantages in pilot visibility of using the armor glass of a fighter airplane for a reflex mirror have already been mentioned. The accompanying disadvantage is that the aperture and hence the volume of the sight must be very large in order to attain the necessary eye relief when large speed rings are used (as in the standard Navy reticle pattern). If the sight can be recessed into the fuselage forward of the instrument panel, however, large aperture, per se, is not difficult to accommodate. The difficulty comes in the volume of sight projecting inside the fuselage into a space already crowded by the instruments mounted on the panel.

In an effort to secure a large aperture in a compact sight of minimum depth the Development Department of the Eastman Kodak Company originated and developed the "Fly's-Eye" Mark 14 sight for use with Navy fighter aircraft under contract with Division 7, NDRC.[3] It consists essentially of an array of many small reticle and collimator units honeycombed together and carefully aligned with each other so that the light from corresponding points on all the reticles emerges parallel over the whole array. Thus, as the observer's eye scans the aperture, passing from one lens to the next, the apparent position of the reticle remains fixed in space except for minor parallax errors of the individual lenses. The small lenses are carefully edged to a shape (usually hexagonal) which permits them to fill completely the area of the array.

The depth of the collimating system is simply the focal length of the individual lenses, and the aperture can be made any desired size independent of the depth.

The principle of the system will be seen in Figure 10. The three essential parts are the

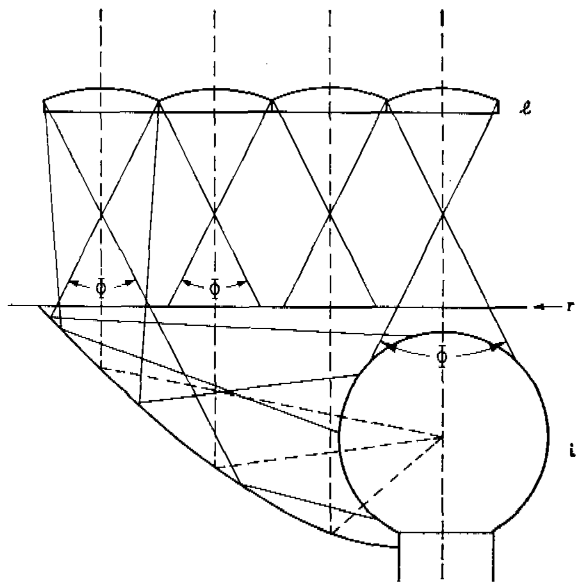


FIGURE 10. Elements of the Fly's-Eye sight.

lens plate l, the reticle plate r, and the illuminator i. The lens plate carries the small collimator lenses, which will hereafter be referred to as *lens elements*. The reticle plate carries the corresponding reticles, one for each lens element. The apparent field of the system is restricted mechanically to that obtained with reticles of the same diameter as the lens elements. Wide fields are therefore obtained only with lens elements of high aperture ratios.

Ideally it should be possible to make multiple lens collimating systems with depths of only 1½ or 2 mm (diffraction becomes troublesome in smaller sizes). But small depths naturally require a great many very accurately adjusted lens elements and reticles, and the practical difficulties of assembly and adjustment by the present methods become prohibitive.

[redacted]

As a sample of a practical depth, the Model G sight has a distance of 45 mm from the reticles to the front vertices of the lens elements. Since the illuminator is necessarily of the order of 50 mm deep, the advantage of further reduction in the depth of the collimator is not great and is not commensurate with the increased difficulties.

Although no models of the multiple lens sight have been constructed for linkage with a lead-computing mechanism, it is as easily adapted for this use as any of the more conventional sights. Either the reticle plate can be moved to put in the lead, or the sight as a whole can be tilted. Designs for both types were made at the Eastman Kodak Company.

12.3 MODELS OF OSRD REFLEX SIGHTS

The optical characteristics of all the OSRD sights have been collected in tabular form in Appendix I to this chapter. Specifications of the optical systems are given in Appendix II and drawings showing the general forms of the optical systems appear in Appendix III to this chapter.

Several sights were designed but not constructed. Others were made into table models (Class B models, Appendix I) for optical testing but not for Service use. The remaining sights were made into production prototypes (Class A models, Appendix I) for testing under Service conditions.

All of the Class A models and a few of the Class B models are discussed in the remaining sections of this report. The pertinent information about the others is included in the appendices to this chapter.

12.3.1 Yerkes L9k (T-95)[1b]

The L9k sight was made in response to a request from the Army Antiaircraft Artillery [AAA] Board at Camp Davis for a sight to be used with the M45 multiple machine gun mount. The sight should be reasonably compact, with speed rings of radii 70, 140, 210, and 280 mils. Long eye relief was not necessary.

The optical system of the L9k sight, with an aperture of 2.75 in., is shown in Figure 11. It is equipped for either daylight or electrical illumination.

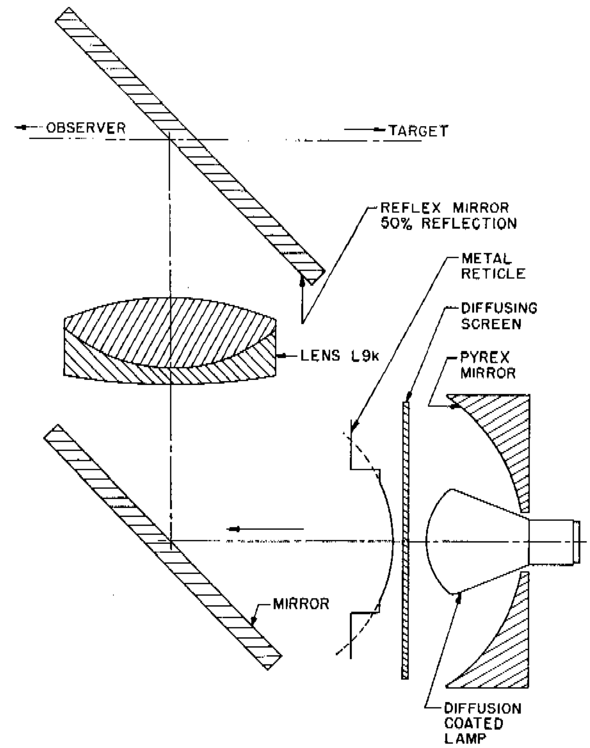


FIGURE 11. Optical system of T-95 (L9k lens).

The sight was built complete with mounting and boresighting attachments. It was sent to the AAA Board and successfully tested on the M45 mount.

12.3.2 Rochester T-94[4]

The T-94 sight was designed for the M45 multiple machine gun turret of the AAA Board and the single 50-caliber antiaircraft machine gun mounted on half-track trucks of the Armored Force for the discouragement of low strafing attacks. Long eye relief was not necessary. Two models were made which were essentially alike except for the aperture of the collimator and the diameter of field.

Both are daylight illuminated with half-reflecting reflex mirrors and single folded optical systems. In both, the collimator lens is a pair of identical cemented doublets with a combined

focal length of 100 mm used with a curved reticle of 31.8-mm radius. The optical characteristics are as follows:

Model 01: 50-mm aperture, 210-mil field (rings only)

$$P_0 = 0.2 \qquad P_{210} = 3$$

Model 02: 60-mm aperture, 280-mil field (rings only)

$$P_0 = 0.4 \qquad P_{280} = 5.$$

A section of Model 02 appears in Figure 12

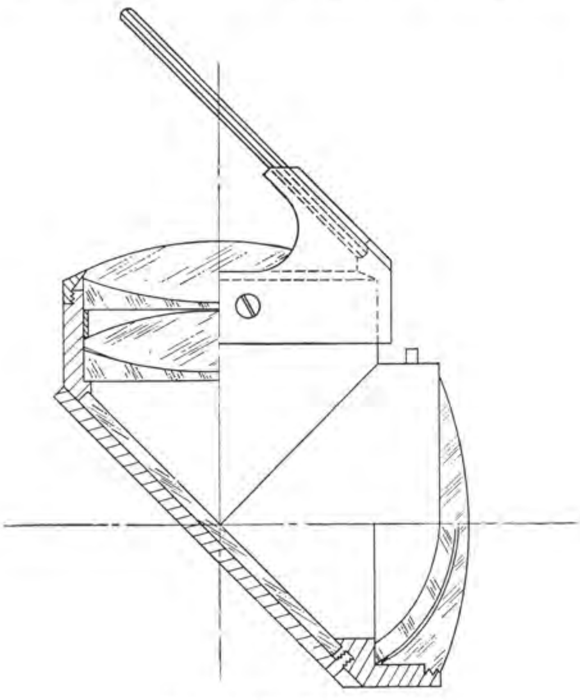


FIGURE 12. T-94 sight.

and a photograph of the sight on its boresighting mount in Figure 13.

Model 02 is provided with an electric illuminator for night shooting consisting of a light aluminum shell with a diffusing surface containing a 3 cp red lamp. The shell bayonets onto the sight over the reticle.

Model 02 was tested on the M45 turret in May and June 1944. Its performance was satisfactory and the sight was adopted.

Pantagraph Mount for Sight

In order to use the machine gun sight on the single truck-mounted gun, it was necessary to mount it with an offset of about 18 in. to clear the smoke cloud at the muzzle when the gun is fired. After much discussion a flexible mount was made. The sight is carried on a parallelogram, two sides of which are parallel to the bore of the gun. The corners are pivoted, and the sight is moved longitudinally with respect

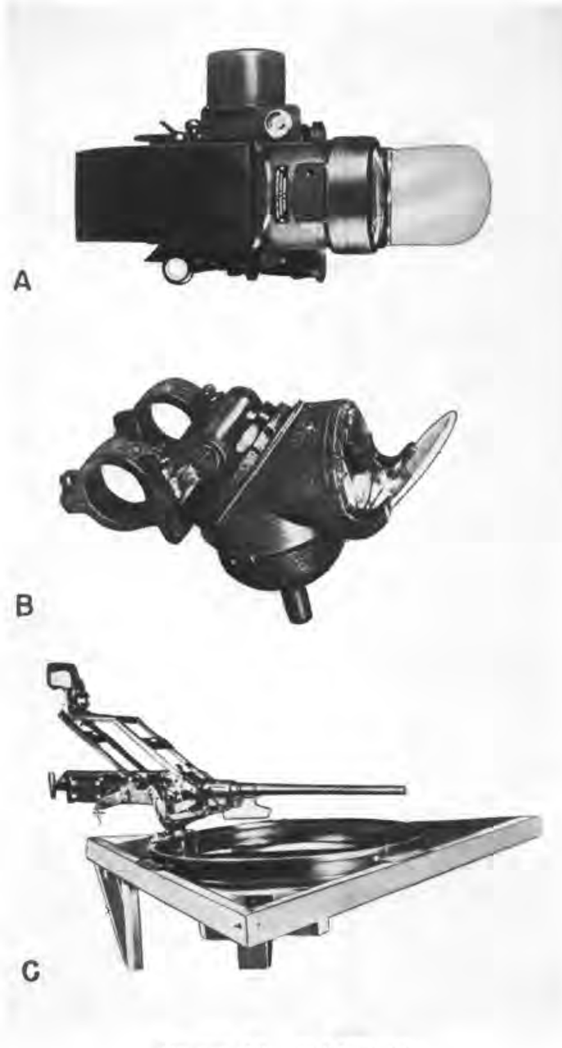


FIGURE 13. T-94 sight.

to the gun by pressure of the gunner's head against a pad located behind the sight. He can thus use it in the most comfortable position, which is a function of the altitude at which he is firing. The mount also serves to absorb the vibration of the gun while it is firing and keeps the sight aligned with the bore. A photograph

of the mount with Model 02 machine gun sight appears in Figure 13C.

A wooden model of the pantagraph mount was made and tested at Fort Knox. Its performance was excellent. Later a metal mount was made, but the war ended before it was tested.

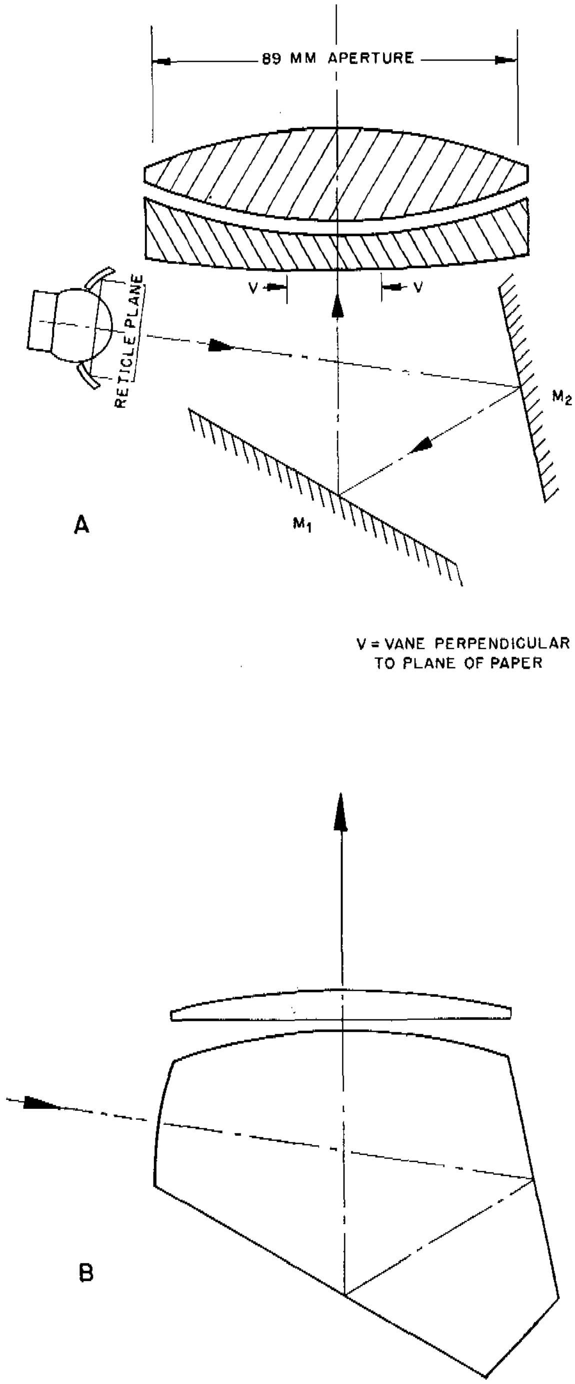


FIGURE 14. A. "Figure-4" sight S-1. B. "Figure-4" sight S-3.

12.3.3 Rochester S-1, S-2, and S-3[4a]

The "Figure-4" sights, S-1, S-2, and S-3, were designed in response to a need for a sight to replace the Navy Mark 8 which was very compact but expensive and optically unsatisfactory. The $f/0.85$ lens had large parallax and chromatic errors and the illumination was both insufficient and uneven.

The principle of the "Figure-4" sights is simply to use a lens of moderate focal length and fold the optical path with two plane mirrors as shown in Figure 14A. The name "Figure-4" comes from the shape of the optical path. The functioning of the various parts will be evident from the drawing. Two points deserve special mention.

The reticle fits between the upper edge of mirror M_1 and the lower edge of the collimating lens. An increase in reticle size necessitates lowering the position of M_1 and hence an increase in focal length. As a result, the apparent field increases more slowly than the reticle size, and the overall size of the sight increases very rapidly with the size of the field. Hence, the "Figure-4" sight is useful for small reticle patterns but its advantages disappear when an attempt is made to use it as a wide-angle sight.

The position of the reticle is such that unless precautions are taken, two extraneous images of it are formed by reflection in the mirror M_1 and the rear surface of the collimating lens. They can be suppressed by carefully limiting the cone of light from the reticle so that it just fills the lens.

S-1

The S-1 sight, Figure 14A, was designed to accommodate a reticle pattern consisting of a central dot and a single speed ring of 70 mils radius. The lens works at $f/2.5$, with $P_0 = 1.3$ and an aperture of 3.5 in. It is a separated doublet made of the most easily procured glasses available.

Because of the simple nature of the reticle pattern, a very efficient illuminator can be used. The source is a 3 cp lamp. The central dot of the pattern is a virtual image of the filament of the

lamp formed in the focal plane of the collimator lens by a small negative lens mounted about a centimeter inside the reticle. The 70-mil ring is illuminated by a spherical mirror with its center of curvature at the center of the ring and a radius of curvature equal to the radius of the ring multiplied by $\sqrt{2}$. The distance from center of curvature to filament is the radius of the ring. The mirror then concentrates a sizable fraction of the light from the filament on the ring in the reticle. Unfortunately, the tangential spread of the light passing through a given point in the ring is insufficient to fill the collimator lens, and it is necessary to use a diffusing surface in the plane of the ring.

A working model of the S-1 sight with the optical parts mounted in wood was made for demonstration. The electrical illuminator could be removed and daylight used instead. A half-reflecting reflex mirror was provided for the purpose and worked satisfactorily.

The model was submitted to the AAF Matériel Center in August 1942. It was adopted and produced in large numbers as the AAF N-9 sight by the Bell and Howell Corporation.

S-2

The S-2 sight was designed for the Navy BuOrd to accommodate the standard Navy reticle pattern with a radius of 150 mils. The focal length was increased to $f/3$, and the resulting sight was rather bulky. Samples were made for the Bureau of Ordnance by the Preston Laboratories.

S-3

In order to reduce the physical size of the reticle required for the Navy pattern, the S-3 was designed as a solid sight. It consists of a single glass lens and a large prism of plastic with one lens surface. The optical path, Figure 14B, is essentially the same as in the S-1 sight, and the dimensions are roughly the same. But, since, the effective focal length in air is l/n times that in plastic, the apparent radius of the reticle is n times as great as it would be with an air system of the same size. By running the radial lines of the Navy reticle pattern into the corners, a square reticle slightly smaller than that of the S-1 sight could be used. The parallactic range for the central dot was 1.3 mils.

Samples of the S-3 sight with a 3.5-in. aperture were made for the Bureau of Ordnance by the Preston Laboratories. The Navy reports that they were not satisfactory because it had been impossible to obtain thick plastic blocks of sufficient optical homogeneity.

12.3.4 Rochester Flightsight[4b]

In the summer of 1942 the Navy Bureau of Aeronautics requested a reflex sight for night use in the F4U-2 equipped with radar. The sight was to present at infinity the radar oscilloscope screen, airspeed indicator, and gyro horizon in addition to a reticle for night shooting. The pilot could then intercept and close with an enemy until he made visual contact, without having to look away from the position where he expected to find him, and without changing the accommodation or endangering the dark adaptation of his eyes by looking at the instrument panel. The instrument constructed at the Institute of Optics in response to the request was termed the *flightsight* for lack of a better designation.

The optical system of the flightsight is shown in the isometric drawing of Figure 15. Only the faces of the instruments are shown. The sight is a two-story affair with the radar tube on the lower level and the airspeed indicator, gyro horizon, and reticle on the upper level. The radar screen is seen through the half-reflecting mirror M_2 by reflection from the fully aluminized mirror M_1. The gyro horizon is seen by reflection from M_2 through the half-reflecting mirror M_3. The airspeed indicator, with the edge illuminated reticle on its face, is seen by reflection from M_2 and M_3.

The faces of the gyro horizon and airspeed indicator are masked, leaving only the illuminated tips of the horizon bar and airspeed hand visible. Four index marks are ground on the glass cover of the gyro horizon and are edge illuminated.

As the pilot looks into the reflex mirror he sees the radar screen with an apparent diameter of about 250 mils, around the edge of which appear the four fixed indices, the tips of the

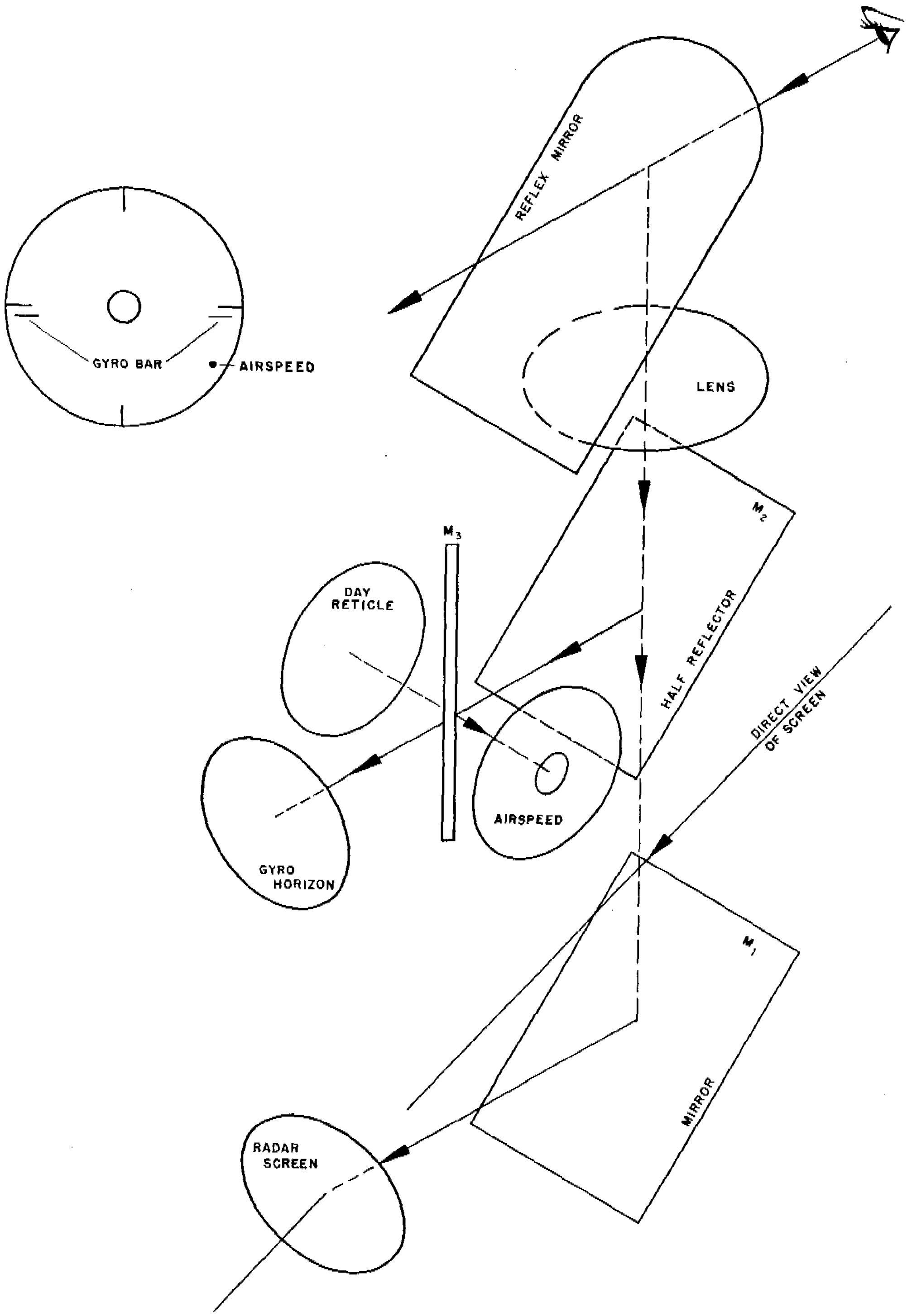


FIGURE 15. Optical system of flightsight.

horizon bar, and the tip of the airspeed indicator. At the center is a 25-mil diameter circle which serves as an aiming point in shooting and an index for the radar indications. The layout of the field appears at the upper left of Figure 15. For daytime use the mirror M_3 is rotated 90 degrees to reflect light from a brightly illuminated reticle of standard Navy pattern into the system. The radar screen can be seen directly through an opening in the housing between the mirrors M_1 and M_2.

FIGURE 16. Flightsight.

The lens is a separated doublet of 3.5-in. aperture and 12-in. focal length with a parallactic range of 0.2 mil. The assembled sight with airspeed indicator and gyro horizon in place, but without the oscilloscope tube, is shown in Figure 16.

The flightsight was delivered to the Bureau of Aeronautics in April 1943 but was not tested in flight until August 1944. It was installed in a JRB airplane, and after one small alteration it performed well except for a slight vibration of the reflex mirror which blurred the fine detail of the radar indication. By that time the need for the device had abated because of the improvement in radar which made it unnecessary to make visual contact before shooting. The mounting of the reflex mirror was altered but was never tried in flight.

12.3.5 Rochester T-67[4c]

In July 1943 the Army Antiaircraft Artillery Board of Camp Davis requested that small reflex sights with exit pupils of 35 mm be designed to replace the small-aperture unit power telescopes then in use on the M-7 lead computer of the 40-mm Bofors antiaircraft gun. The T-67 sight was designed and constructed at the Institute of Optics for the purpose. Three models, 01, 02, and 03, were made, which were identical in everything except the illuminators.

The optical system from reticle to reflex mirror is quite conventional and is shown in the drawing of Model 03 in Figure 17. The lens has a 40-mm aperture and 120 mm focal length. The parallactic range P_0 is 1 mil. The reticle

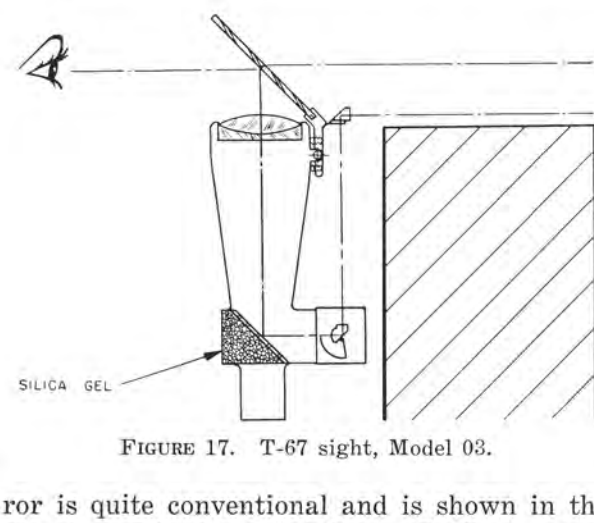


FIGURE 17. T-67 sight, Model 03.

pattern consists of a single line 100 mils long, either horizontal or vertical, for sighting in altitude or azimuth respectively.

In all three models the principal illuminant is daylight from the target area, and half-reflecting reflex mirrors are used. The reticle is placed as low as possible to keep the moment of inertia around the mounting point to a minimum—a point of some importance on a violently recoiling gun when the sight is linked to a delicate mechanism. The light from the target area is intercepted before reaching the reticle directly by parts of the gun. A simple system of prisms with cylindrical lens surfaces is therefore provided to conduct the light from just below the line of sight to the reticle.

Auxiliary illumination for night conditions is provided in Models 01 and 02 by electricity. In Model 01, the change-over to electrical operation is made simply by sliding the last prism of the daylight illuminator from between the lamp and the reticle. In Model 02 the electric illuminator is screwed on in place of the daylight illuminator when wanted.

The night illumination of Model 03 (see Figure 17) is obtained from a fluorescent material bombarded by α particles from an external source of radium. The phosphor is coated on a cylindrical arc located directly behind the reticle which is pivoted on its own axis and can be rotated by an external knob. The radium is rolled in gold foil to a concentration of 0.20 mg per sq cm. Two strips of the foil 1.5 mm wide are mounted on the back of the reticle, one on each side of the straight line opening. The α particles from the radium excite the phosphor directly behind the opening and the emitted light illuminates it to a maximum brightness of about 1 millilambert. The brightness is controlled by spraying a thin wedge of polystyrene on top of the phosphor, the thickness changing as the cylindrical surface is rotated past the reticle slit. As the polystyrene becomes thicker the intensity of α-particle bombardment diminishes. A range of about 100 to 1 in reticle brightness is attained in this way simply by turning the external knob. When the fluorescent illumination is not being used, the cylindrical arc with the phosphor is turned completely out of the optical path and at the same time is removed from the vicinity of intense bombardment.

The usual type of radium luminous paint could not be used here because the concentration of radium required to produce the necessary brightness would destroy the phosphor in a few weeks. With the external source of α particles, bombardment of the phosphor takes place only while the phosphor is being used. Tests indicate that after about 1,400 hr of continuous use the bare phosphor, i.e., no plastic cover, loses half its brightness.

The three T-67 sights were successfully tested at Camp Davis. Four slightly different models with electrical night illumination were produced in considerable numbers by the Argus Corporation with designations M-21 to M-24. M-21 and M-22 are azimuth and elevation sights for the M-7 lead computer on the Bofors gun. M-23 and M-24 are azimuth and elevation sights identical with M-21 and M-22 except for the mounting parts, which are altered to fit the M-55 double 40-mm antiaircraft gun mounted on a tank chassis.

12.3.6 Polaroid $f/1.6$ Sight

The Polaroid $f/1.6$ sight was designed with a plastic optical system to be interchangeable with the Navy Mark 8 sight. It had an aperture of 3.5 in. and the optical system was folded once by means of a mirror. The lenses were mounted as a unit in a plastic sleeve which slipped into the cast magnesium housing, maintaining the elements in alignment with each other. The external appearance of the sight is shown in Figure 18.

The sight was tested by the Navy Bureau of Ordnance. The parallax errors were much smaller than those of the Mark 8 sight but showed a marked temperature dependence.

12.3.7 Mount Wilson Bowen Sight[2a]

Two models of the Bowen Sight were made for testing in the AT-6 and the P-51 B aircraft respectively.

Bowen Sight for AT-6 Aircraft

The first model of this sight was built by

the Observatory independently of Contract OEMsr-101. It was designed specifically for the AT-6 training plane, since drawings were not immediately available for a combat plane.

The optical parts are mounted on a single casting, as shown in Figure 19A. This is designed to follow closely the shape of the frame surrounding the windscreen so that when it is mounted in the airplane it adds little or no obstruction to the pilot's vision. The optical system is inclined at such an angle that the mirror is seen edge on from the normal eye position, as in Figure 19B.

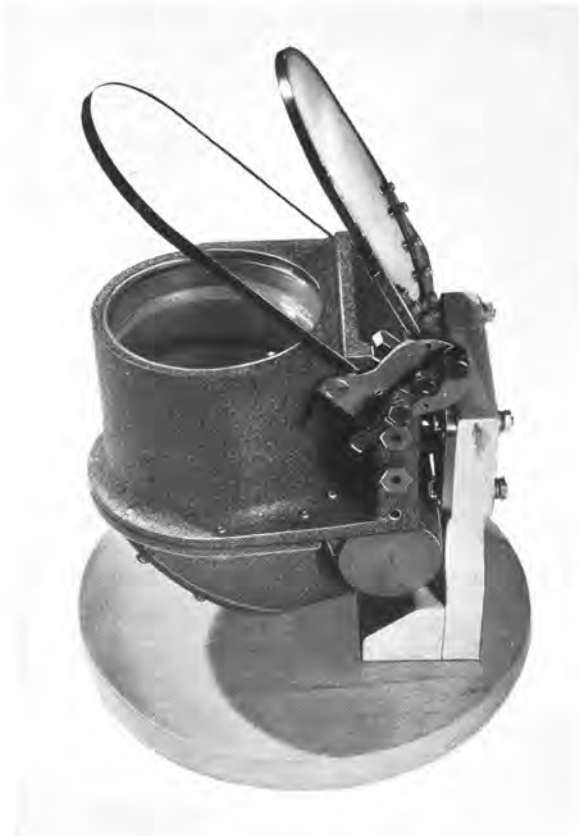


FIGURE 18. Polaroid $f/1.6$ sight.

The focal length of the spherical mirror is 9 in. (radius of curvature 18 in.). The mirror itself has the shape of a half circle, and was cut from a circular mirror 9 in. in diameter. This shape gives good visibility in the lower corners of the field, and vignettes only those parts of the reticle which are not actually used.

The field is adequate to provide for a reticle speed ring of 400 mph (400 mils diameter), and with a focal ratio of $f/2$. The parallax due to spherical aberration is held to about 1 mil of angle. The exit pupil has a diameter of 4.5 in., and is located about 12 in. back of the reflex plate, or very nearly at the normal position of the pilot's eye. A view from this position is shown in Figure 19B. This was taken with a wide-angle lens, and to obtain correct perspective the photograph should be viewed from a position 4 in. above the paper.

The reticle pattern is cut in a thin metal shell which fits over the upper lens of the illuminating system. To conserve light, the upper surface of this lens is aluminized, leaving clear bands somewhat wider than the rings of the reticle. When Figure 19B was made the reticle itself was not available, and the circles shown

FIGURE 19. Bowen sight for AT-6.

are images of the clear bands in the reflecting coat. Although they are far too wide, they show the correct positions of the various rings of the reticle pattern. These have diameters of 400, 300, 200, and 100 mils. The inner edge of the smallest ring shows approximately the position of a 70-mil circle. This was for some time the largest pattern available in any standard sight. A 100-mil circle is now standard for fixed sights.

This model was tested in January 1944, at Matagorda Peninsula, by several experienced pilots. Firing tests were carried out on towed targets. Once the sight had been properly harmonized, the scores compared favorably with those made with standard sights.

Although the 400-mph reticle speed ring could not be used effectively in an AT-6 ship, the pilots were able to form a judgment whether so large a circle would be useful in a combat plane. Their conclusion was that it would lead to confusion, and that the reticle should contain only the 100 and 200 mph circles.

The pilots who made the tests spoke very highly of the excellent visibility of the reticle image, due mainly to the size of the exit pupil and its proximity to the pilot's eye. A lens system to give equivalent visibility on a 200-mph reticle would require an aperture of about 7 in. Another factor improving vision is the use of the large reflecting plate free from obstructions near the line of sight. The target as well as the image is seen through the glass instead of to one side of it as in standard sights.

One criticism of the model was the feeling of the pilot that the presence of the mirror and reflecting plate so close to his face crowded and confined him so that he could not reach the instrument panel with sufficient freedom. The reduction in size of the instrument due to the use of a 200- instead of a 400-mph reticle speed ring would aid somewhat in modifying this difficulty, but the sight would necessarily be considerably larger than those in general use.

A second objection which was not foreseen was the reduction in contrast of the field of view caused by sky light reflected into the pilot's eyes by the glass plate. A marked improvement resulted from painting the supporting bracket black and removing a zinc sulfide coating from the glass. The pilots did not consider either the reduction of visibility due to the spherical mirror or the crash hazard of the glass in front of the operator as serious. The sight used in the P-38 was considered much more dangerous.

As a result of the tests at Matagorda Peninsula it seemed desirable to construct a second model designed for a combat plane, eliminating so far as possible the objections which have been described.

Bowen Sight for P-51 B Aircraft

The second model, shown in Figure 20, introduced the following modifications:

1. Inversion of the optical system, placing the spherical mirror below and turning the glass reflecting plate roughly parallel to the windshield, thus reducing sky reflections.
2. Reduction of the reticle speed ring size to 200 mph, instead of 400 mph.
3. Support of the reflex plate on a separate yoke which can be rotated as a unit for boresighting; this replaces individually adjustable brackets.
4. Simplification of the lighting system in the interest of greater compactness.

The first of these changes was successful in reducing reflection of general sky light from the reflex plate. At the same time it leads to a design which fits more compactly into the plane. But it has three disadvantages which will have a bearing on the design. (1) Light from the reticle passes through the reflex plate at a steeper angle, causing astigmatism which is noticeable under some conditions but probably not of practical significance; (2) the spherical mirror is placed in a more exposed position; and (3) in the present instrument it is possible at certain angles to see a weak image of the sun reflected by the reflex plate, the mirror, and the reflex plate again.

The modified system for illuminating the reticle retains the principle of limiting the relative aperture of the mirror, but accomplishes this by means of a diaphragm placed a short distance behind the reticle. This diaphragm has openings similar to the reticle pattern but enough wider to admit cones of light of the desired angle. This method provides a fairly satisfactory substitute for the more elegant de-

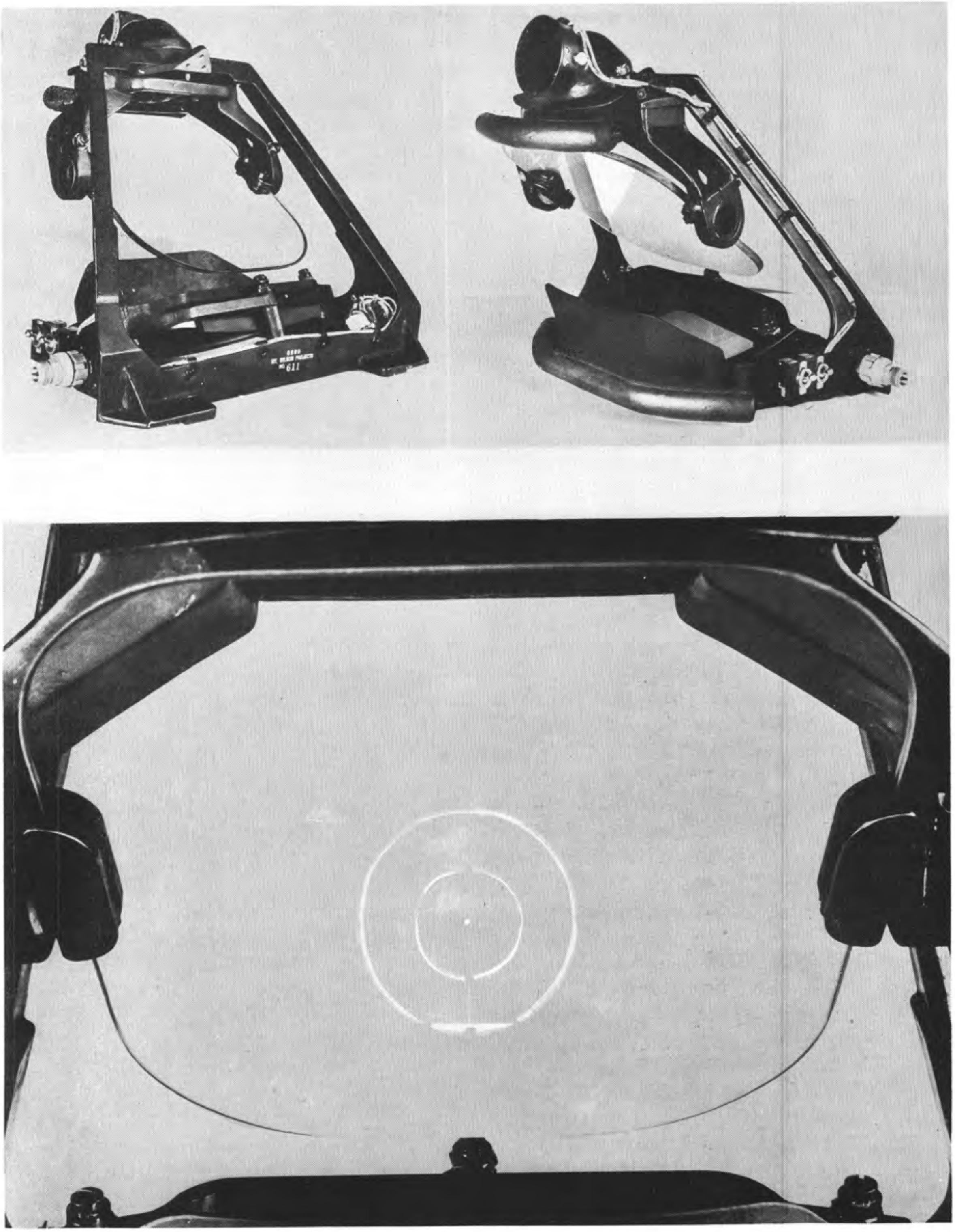


FIGURE 20. Bowen sight for P-51 B.

sign described above. It is not clear whether the slightly inferior optical performance is justified by the smaller size of the lighting unit.

As in the first model, the shape of the main frame of the instrument follows closely the supports of the enclosure of the aircraft for which it is designed. Both models are so planned that they can be installed with little or no modification of the airplane.

Upon completion, this model was sent to Wright Field where it was mounted in an airplane and tested in flight. It was then forwarded to Matagorda in October 1944 for further testing.

As a result of the latter tests a few modifications in the design were found to be advisable. The forward pair of bolts used for azimuth adjustment should be more easily accessible. The reticle image was not intense enough under all conditions. It is believed that this can be improved by minor refinements in the design of the lighting system. A cover of some sort should be provided to protect the mirror surface from damage. The mirror should also be shielded from direct sunlight more completely than in the present model.

The sight was used in target firing with 4,000 rounds of .50-caliber ammunition. The towed targets presented areas of from 64 to 80 sq ft, and the results, calibrated for full-sized targets, showed 28 per cent hits. It was thought that better results would undoubtedly have been obtained had full-sized targets been available. Assessment of the film showed much smoother attacks than when firing with other fixed sights, due to the greater eye freedom afforded. No restriction to the forward visibility of the pilot was noted.

These flight tests indicated that use of the Bowen sight would result in substantial increases in scores for aerial gunnery over the results obtained with other sights.

The greatest value of the Bowen sight appears to lie in the easy visibility of the reticle with both eyes and the lack of obstruction in the neighborhood of the line of sight. Its remarkable ability to handle large reticles would not seem to be of great advantage for fixed sights, since pilots have concluded from firing tests that reticles with speed rings larger than 200 mph are not needed. The Air Forces are rapidly converting to computing sights and it is probable that further development work on fixed sights is not warranted. On the other hand, the advantages of the optical system in the Bowen sight for use in lead-computing sights, in which the reticle is moved over the whole range of possible leads, are worth serious consideration, and the hope that its advantages may be incorporated into computing sights is expressed in the Matagorda report.

12.3.8 Mount Wilson Hayward Solid Sights, S-1[2b]

The solid reflector sights developed at the Mount Wilson Observatory are simple compact units which employ daylight illumination, designed for use where large exit pupils and long eye relief are unnecessary. Five different models for specific uses were made and will be discussed below.

The optical systems for all were essentially identical although two aperture sizes, 1 in. square and ⅝ in. square, were used, with the same focal length of 0.97 in. The ⅝-in. aperture system is shown in Figure 21. The 1-in. aperture models were similar except for the fact that there was not room to fold the optical path, and the reticle was placed on a surface parallel to the collimating mirror. A 45-degree prism or mirror above the reticle reflected the illuminating light from the target area into the sight.

Solid Sights for the M-1 Rifle (Two Models)

The standard Service rifle is not suited to deflection shooting at rapidly moving targets like airplanes because there is no device for setting in the correct lead. The solid reflex sight for the M-1 rifle was developed to fill this need.

The first model had a clear aperture 1 in. square and a reticle in which the largest circle had a radius of 160 mils. Two later models had an aperture ⅝ in. square and an equivalent focal length of 0.97 in. A mounting was designed in which the sight was clipped directly to a standard Garand rifle and held by spring

hooks, but since this did not appear to be thoroughly satisfactory, another mounting was built in which the sight was clipped to a short track fastened permanently to the rifle. Figure

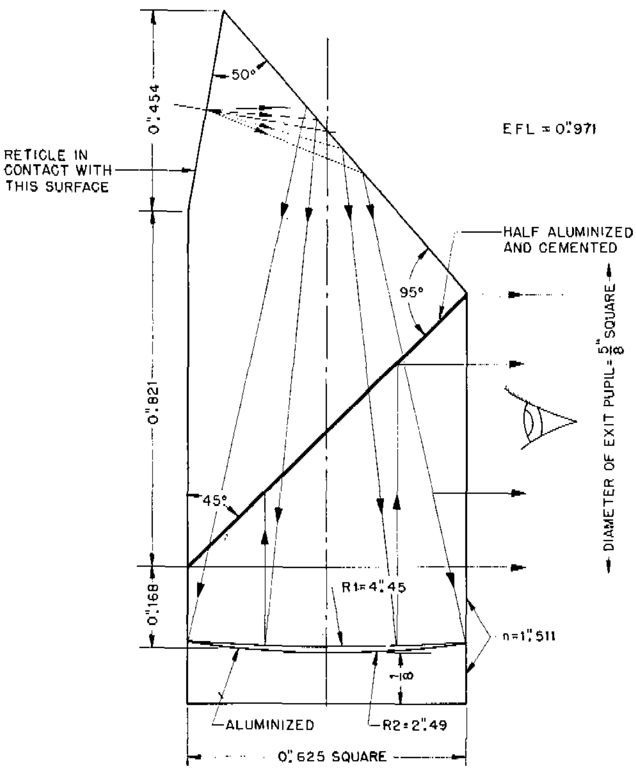


FIGURE 21. Hayward solid sight, ⅝-in. aperture.

22A contains two photographs of a wooden mockup of the mounting, showing the method of clamping the sight in position with a single lever. In the model tested, the track was mounted on a saddle which clamped directly to the metal of the gun, instead of being screwed to the stock as is indicated in the photographs.

The sight was tested at a military range with 72 rounds of firing. It proved to be sufficiently rigid, and after adjustment of the reticle, a typical series of eight shots fell within a circle the diameter of which was about 3 mils, or the size of the central dot of the reticle pattern. This would be quite adequate for use against airplanes, but against stationary targets the accuracy was less than that obtained with open sights. It seems probable that the scatter was due rather to imperfect visibility of the reticle than to the sight itself. Light for the reticle was taken from an area about 10 degrees above the target which under the conditions of the test formed a dark background. This difficulty limits the application of the sight in its present form, although against targets in the sky or near the horizon the visibility of the reticle is satisfactory.

Solid Sights for AA Guns

Two samples of solid sights of 1 in. square aperture were made for tests with antiaircraft guns at Camp Davis for the AAA Board. The reticle was illuminated by light from the target area which was reflected into the sight by an external 45-degree mirror. While the assembly was light, it was not as compact as that of the ⅝-in. rifle sight.

Tests of the sights indicated that they performed well, but the light reflected from the glass surface nearest the eye tended to reduce the contrast of the field.

Solid Sights for Rockets

The optical parts for twelve solid sights with an aperture of ⅝ in. were completed and sent to the California Institute of Technology for experimental use in aiming a hand-held device for launching rockets. No formal report on these sights has been made. The devices for which they were intended were discontinued.

Solid Sights for the Navy Mark 17 Gunsight

At the request of the Bureau of Ordnance a solid reflector sight was designed and constructed for use on the Mark 17 gunsight. This is a mechanism which is connected to turret guns in a bomber and introduces the necessary deflection for an own-speed sight by means of the vector principle. Since in this case the gunner keeps the reticle centered on the target, a large reticle pattern is not required, but a large visible field is still desirable, and a large aperture is valuable in allowing freedom of eye position.

The finished model of this sighting unit is shown in Figure 22B. The upper fifth of the glass block is a separate prism, cemented to the main block with the thin metal reticle between. Light from the sky enters this upper prism

from the front and is reflected downward through the reticle. This is the most compact of the designs developed. The very high relative aperture (about $f/1$) is optically satisfactory, but presents serious problems of illumination. When viewed from different parts of the aperture the reticle is illuminated by different areas of the sky. This increases the chance that some obstruction will cut out or reduce the light. It also makes less effective the great advantage of illuminating the reticle by light from the direction of aim, the advantage being that the contrast between reticle and field is fairly constant even when the brightness of the field varies widely.

The extreme lower end of the glass block is

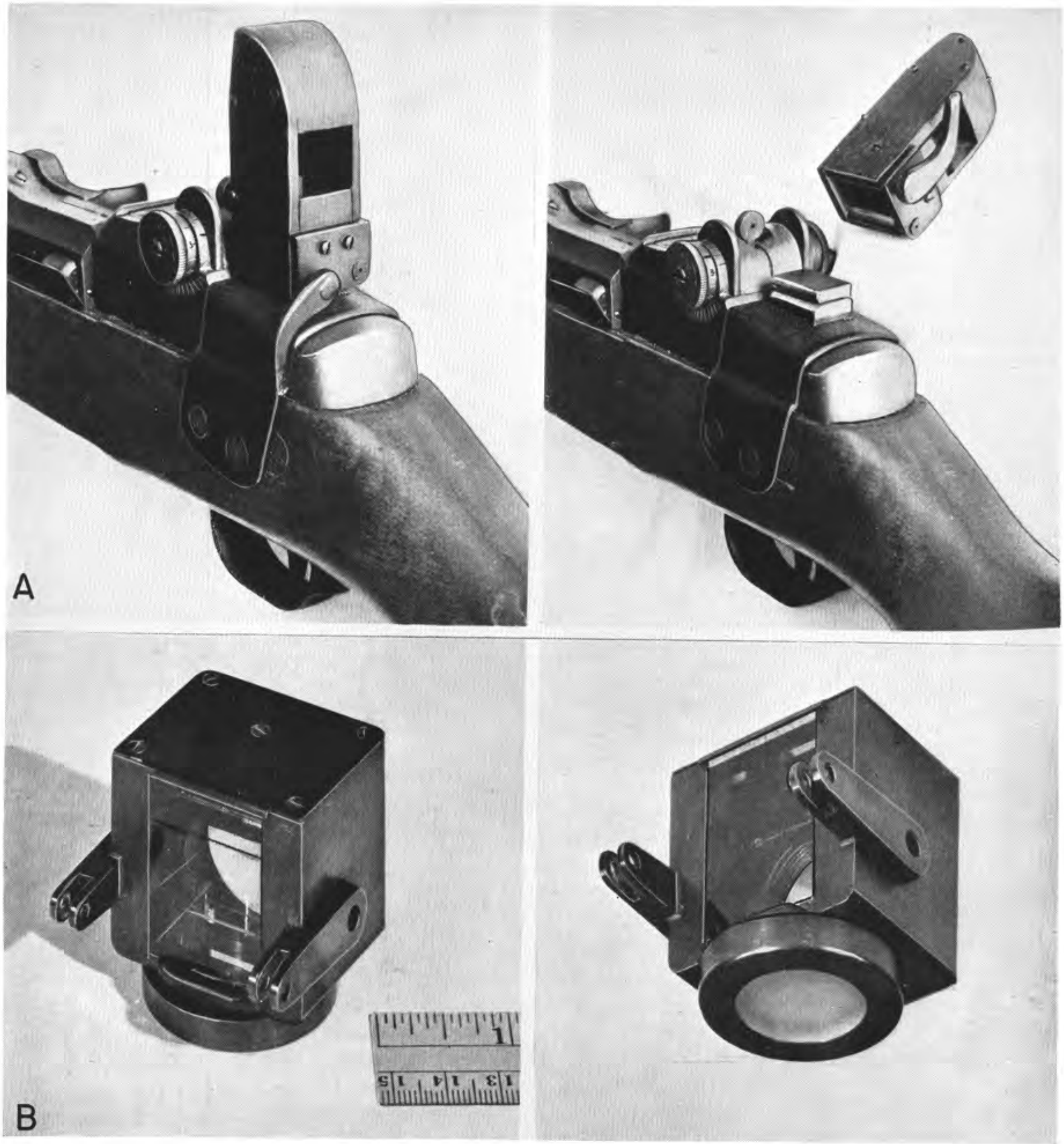


FIGURE 22. A. Solid rifle sight, wooden mockup. B. Solid sight for Bureau of Ordnance.

cut round in section, so that the spherical mirror fits against it and is held much as a lens is ordinarily mounted. The sides of the entire glass block are cylindrical in shape, the axis of the cylinder being that of the optical system. These cylindrical surfaces fit the walls of the mounting which is cut from a single piece of steel. The glass is cemented in place with balsam, giving a solid construction which reinforces the cemented 45-degree surface of the glass.

A sight utilizing a half-silvered mirror was developed elsewhere at about the same time the solid sight was being investigated at Pasadena. This sight, which uses a concave half-silvered mirror through which the field is viewed, has several marked advantages, being light in weight, well illuminated, and easy to manufacture. It was found to be better adapted to use on the Mark 17 gunsight than the model of the solid sight which had been built. The solid sight could be made much lighter than at present by the use of an aluminum mounting, and the illumination could be varied within wide limits. Under the circumstances, however, it did not seem desirable to continue development of the solid sight further without securing additional information concerning the requirements.

12.3.9 Yerkes Solid Sight M-16[1c]

Although no model of the M-16 solid sight was built, it should be mentioned here. Inspection of the drawing in Appendix III to this chapter will show the lens which has been added to the solid Mangin design. This addition has enabled the designer to reduce the off-axis aberration to such an extent that the parallactic range for a circle of 210 mils radius is only 0.5 mil. To reduce the weight to a minimum the materials used were CHM and styrene plastics. It is regrettable that no samples were constructed.

12.4 EASTMAN FLY'S-EYE SIGHT[3]

Although it was developed under the auspices of Division 7 of NDRC, the Fly's-Eye sight is so directly related to the subject of this report that a full account of it is included.

The principle of the sight has already been described. Several different experimental models were constructed, culminating in the Mark 14 illuminated sight, Model G, which is the production prototype. Since Model G represents a combination of the best features of its predecessors, the earlier models are not described here. However, several problems encountered in the course of the development of any sight of the multiple lens type will be discussed. Model G is shown assembled in Figure 23, and disassembled in Figure 24.

The lens plate is made up of hexagonal aspheric molded lens elements 15.67 mm in diameter (inscribed circle) cemented on a plane-parallel glass. The effective aperture is a rectangle 118 by 141 mm. An individual reticle etched through a curved shell of copper is mounted below each lens element on an Invar reticle plate. The illuminator consists of four 50-w ceramic coated lamps at the foci of four parabolic mirrors which are carefully fitted together to fill the whole area behind the reticle plate. The heat of the lamps is removed by filtered air circulated through the instrument at a rate of 15 cu ft per min. The reticle brightness B_1 can be adjusted from zero to about 26 lamberts by varying the resistance in series with the illuminator. The armor glass in the airplane serves as reflex mirror.

The reticle is of the standard Navy pattern with a central dot and two rings of radii 50 and 100 mils. Four radial lines extending from 25 to 150 mils in the 12 o'clock, 3 o'clock, 6 o'clock, and 9 o'clock positions complete the pattern.

The parallax errors are rather complicated and cannot be readily specified in any simple form. As the eye moves across the exit pupil it crosses successively a series of lens elements along chords at random distances from their centers. The apparent parallax of any one lens element depends upon the chord which the eye traverses and the field angle, and is different for the circles and the lines of the pattern. The effect observed is aptly described as an apparent "wriggling" of the reticle pattern. The use of aspheric elements gives a negligible wriggle to the central dot of the pattern, and a maxi-

mum of the order of 3 mils parallactic range at the edge of the field. Chromatic aberration is uncorrected and results in a spread of about 4 mils between C and F at the edge of a lens element.

The sight is held in a boresighting mount

FIGURE 23. Mark 14 Model G sight.

and is designed to fit into an opening in the airplane fuselage forward of the instrument panel and directly under the armor glass. In this position it is completely out of the way and offers no obstruction whatever to the pilot's field of view. This is the great point of superiority of the Fly's-Eye sight and is the principal justification for the greater complexity of the design. In most airplanes, however, some planning of the layout of the instrument panel is required to provide space for the sight.

12.4.1 General Problems of Design and Construction

Many of the problems encountered in the development of the various models of Fly's-Eye sight at Eastman Kodak are inherent in this type of sight and hence are of general interest. A few of them are therefore described briefly below.

LENS PLATES

All lens plates (with the exception of the preliminary model to demonstrate the multiple lens principle) were made by cementing hexagonal lens elements onto a plane-parallel glass plate. The division line between neighboring elements was kept as fine as possible to avoid fluctuations in brightness as the eye crosses from one element to the next. The possibility of molding the whole plate in one piece is an at-

FIGURE 24. Mark 14 Model G sight disassembled.

tractive one, but will not be practicable in glass until methods of molding large pieces have been developed. The use of plastics, however, may deserve serious consideration.

Lens elements for use on the lens plate should have, as far as possible, the attributes desired in the usual reflex sight lens. In addition, they must be in one piece with a plane back surface for cementing onto the plane-parallel plate. The latter requirements impose a serious handicap on the designer's efforts to attain the necessary

corrections. Finally, the lens elements must be adapted to easy production in large numbers.

Four types of lenses were used in the various models of Kodak sights:

1. A cemented achromat, $f/2.92$.
2. A simple lens, $f/2.92$, of EK-11 glass, characterized by a high index and low dispersion. $n_D = 1.69677$, $\nu = 56.1$, $P_0 = 2.4$.
3. A simple lens with a hand-figured aspheric surface, $f/2.92$, of the same glass as lens No. 2.
4. A simple lens with a molded aspheric surface, $f/2.43$, of cane glass. $n_D = 1.51$.

Of these, the hand-figured aspheric lens (No. 3) gave the best performance except for chromatic aberration. Unfortunately, the glass, which was in part responsible for its superior correction off axis, could not be molded. Since the hand figuring of the aspheric surface is not a practical production method, the somewhat less satisfactory lens No. 4, which could be molded, was adopted as a production prototype. It was considered that the chromatic aberration was not too serious since it could be considerably mitigated by the use of a light orange or yellow filter to eliminate the high-dispersion end of the spectrum.

Once the lenses have been shaped and edged, the elements have to be carefully cemented in place. Since it would be most undesirable in production to have to adjust the reticles in the reticle plate individually, the lens elements must be positioned with an accuracy of about 0.02 mm. A jig was designed to accomplish the positioning with the requisite accuracy, but was not made because it would be too expensive for use on only a few samples. With its use in manufacture, however, it is expected that interchangeable lens plates could be produced.

Reticles

The original method of making the reticle plate for the multiple lens sight was simply to photograph a reticle at infinity through the lens plate. An image of the reticle pattern was thus obtained in its proper position behind each lens element. This method was satisfactory for reticles of 50 mils radius or less, but failed when used for the larger reticles of the standard Navy pattern because the individual reticles could not be curved to fit the focal surfaces of the lens elements.

In an effort to obtain better approximation to the focal surface, a two-layer photographic reticle plate was tried. The outer parts of the reticle pattern were photographed on one plate with a circular clear area at the center of the pattern. The inner parts of the pattern were photographed on a second plate below the first and viewed through the clear areas. A two-level reticle was obtained which was quite satisfactory for the rings in the pattern, but showed a wriggling break in the radial lines as the eye scanned the aperture. The result was considered unsatisfactory and, in spite of the ease of manufacture, the photographic reticle plate was abandoned.

In its place, reticles etched through a thin curved metal shell were used. They were shaped to coincide with the surface of best focus for radial lines at 150 mils from the center where the lines ended, and with the surface of best focus for rings from 100 mils in to the center. The metal reticles were completely transparent, durable, and heat resistant, but, like the lens elements, had to be assembled individually on the reticle plate with considerable precision. No quick method for positioning them in production has been worked out.

Illumination

The difficulties of electrical illumination are encountered in their worst form in the multiple lens sight. The total reticle area to be illuminated is large and devices for concentrating light on the lines of the reticle pattern are out of the question because of the great numbers of reticles used. It is regrettable that the position of the sight in the airplane makes the use of daylight illumination extremely difficult.

Two methods of illumination were tried. The first was to place a small lamp in a white-walled cavity behind each reticle. The illumination was insufficient because of the low efficiency of the small lamps, and in spite of its compactness the system had to be abandoned.

The second form of illuminator consisted of several lamps with highly diffusing bulbs at the foci of parabolic mirrors. The lamps were of such size that any ray through a lens element

[redacted]

and through any point in the corresponding reticle would terminate on a bulb either directly or via reflection from one of the parabolic mirrors. By carefully fitting square mirrors together, the whole reticle plate was provided for, without any dark spots. The brightness of the reticles was then the brightness of the diffusing surfaces of the bulbs.

As was mentioned, 200 w are consumed by the four lamps of the illuminator of the Model G sight at full brightness, and some cooling device was necessary to prevent the sight from going up in smoke. Air circulation was provided by a combined centrifuge and blower. The purpose of the centrifuge is to filter the air, and in particular, to remove the particles of salt prevalent in ocean air, since it is quite certain that the metal parts of the sight, and especially the reticles, could not long withstand the corrosive action of warm moist salt air.

Provision was made for varying the reticle brightness continuously from zero to 8.6 millilamberts, and in steps of 0.497 in the logarithm of the brightness to a maximum of 26 lamberts. Since only about 10 per cent of the light is reflected by the reflex mirror, the apparent brightness of the reticle pattern is at most only 2.6 lamberts greater than that of the target area. The brightness should be satisfactory against the usual clear blue sky or a dark overcast, but seems definitely low for use against a bright translucent haze or in the neighborhood of the sun.

12.5 RECOMMENDATIONS BY NDRC

1. Further studies of the Lens-Mangin sight, the Bowen sight, and the Fly's-Eye sight should be made to determine which is best adapted for use in aircraft, taking into account space occupied, aperture, diameter of field available, brightness of reticle attainable, possibility of reflecting the collimated beam from the armor glass, and finally, ease of construction and cost.

2. Solid glass sights should be developed further, with full attention to means for increasing the contrast between reticle pattern and background when sky illumination is used. This should include studies of high-efficiency, cemented, partially reflecting films and the use of quarter-wave plates to increase brightness.

Chapter 13

STADIAMETERS

By *Theodore Dunham, Jr.*[a]

THE RANGE of a distant object may be measured with a rangefinder, which depends on differences in apparent direction at the two ends of a known base line within the instrument itself, or it may be determined with a stadiameter, which depends on measuring the apparent angular size of the object and comparing this with known dimensions of the object. Rangefinders have the advantage that they require no information about the size of the target, but they are large, cumbersome and expensive, and their use is restricted by this fact. Stadiameters are small and inexpensive, so that they can be used under a great variety of circumstances, but they are limited in their usefulness by the fact that the size of the target must be known. Moreover, the target must be oriented with its long axis nearly perpendicular to the line of sight, otherwise a cosine factor enters which cannot usually be estimated with accuracy.

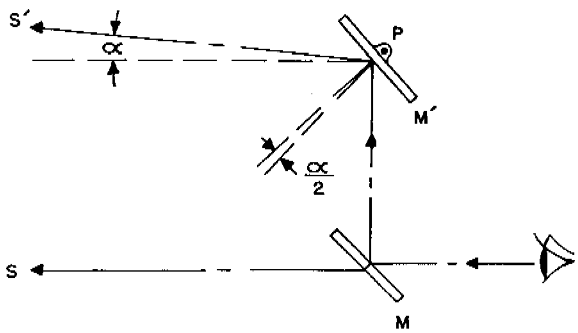


FIGURE 1. Optical system of 1× stadiameter.

Stadiameters have one marked practical advantage over rangefinders, namely that no accurate aiming of the instrument is necessary. The target may appear anywhere in the field where the two images can be set in contact.

The marked simplicity of stadiameters, as compared with rangefinders, has lead to the development of three types at the University of Rochester[1] under Contract OEMsr-160 for a variety of applications.

13.1 UNIT-POWER STADIAMETER

This stadiameter was orginally designed to permit the pilot of one aircraft to fly at a specified distance behind another aircraft in a certain tactical maneuver. The wing span of the leading plane was of course known. Unit power was entirely adequate for this application, since it was merely necessary to hold the spacing between the two aircraft constant within 5 per cent, at a range of about 1,000 ft. A precision of 1 mil in measuring angles is obviously adequate in this case.

Figure 1 shows the optical system. The observer looks directly at the target through the mirror *M*, which is coated to transmit and reflect approximately 50 per cent (see Section 9.5 for a description of the technique for depositing high-efficiency 50-50 coats). The observer also sees the target by double reflection from the totally reflecting movable mirror *M′* and the mirror *M*. *M′* is pivoted about an axis perpendicular to the plane of the paper at *P*. When the two mirrors are parallel, the two lines of sight,

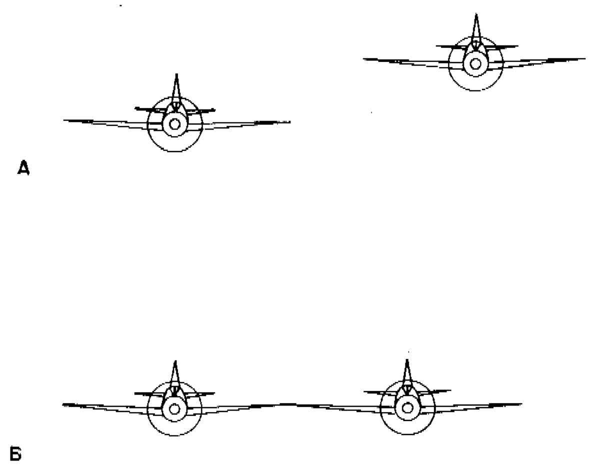


FIGURE 2. Appearance of target in stadiameter. A. Incorrect setting. B. Correct setting.

[a] Chief, Section 16.1, NDRC.

S and S', are parallel, but when M' is turned through an angle $\alpha/2$, S' is deviated through an angle α with respect to S. This causes a doubling of the image of the target, by an angle α. In general, with any random setting, an airplane may appear as in Figure 2A. By adjusting the angular rotation of M', and by rotating the entire instrument about the line of sight, it is easy to bring the two images into contact, so that the appearance is that of two planes flying with the wing tips touching, as in Figure 2B.

FIGURE 3. Photograph of 1× stadiameter.

The angle of deviation α may then be read from the calibrated drum and, if the wing span of the plane is known, the range can easily be calculated. A predetermined distance can be maintained by setting the angle α to the required value, and then maintaining the distance so that the two images appear to fly with the tips of their wings in contact.

The angular setting of mirror M' is controlled by an arm and tangent screw, with an engraved dial reading in mils (thousandths of a radian). The fixed mirror M is adjustable about an axis perpendicular to that on which M' turns, so as to make the two images coincide exactly when they are superposed. The reflectivity of M is such as to make the two images equally bright, but the coating introduces a slight color, so that the two images can be readily distinguished. The instrument is protected by a glass window and is made waterproof. Figure 3 shows the complete instrument with rubber eyecup, calibrated drum, and index mark. The total weight is 8 ounces.

The drum on the tangent screw has fifty divisions 2 mils apart. The total range of the instrument is 300 mils. The field of view is 18 degrees. Settings can be reproduced to somewhat better than 0.5 mil. The zero point is set on a distant object by adjusting the relation of the engraved ring to the knurled knob on the screw.

This stadiameter has been used in a number of experimental applications. In addition to measuring distances between airplanes, stadiameters have been successfully used for checking close radar ranges, for station-keeping between ships, and for establishing the distances between ships and floating targets in experimental tests conducted under Division 6.

Fifteen units of the instrument were made by the U. S. Management and Engineering Company. These have been distributed as samples to the National Bureau of Standards, the Armament Laboratory (AAF) at Wright Field, the Frankford Arsenal, the Armored Force Board at Fort Knox, the Antiaircraft Service Test Section, Ground Forces Board No. 1 at Fort Bliss, the Bureau of Aeronautics, the Bureau of Ships, the Bureau of Ordnance, and the Office of Research and Development in the Navy.

13.2 THREE-POWER STADIAMETER

An application in the Southwest Pacific suggested the need for a stadiameter capable of higher precision than that just described. In photographic reconnaissance it was necessary for F-5 aircraft to fly at high altitude on parallel courses 6 miles apart. At this distance the length of the fuselage of the aircraft subtends an angle of only a little more than 1 mil. It seemed likely that settings could be made with sufficient accuracy if the instrument were designed to display an erect image with 3× magnification. Angular displacement of such a system causes only twice as great an apparent displacement of the target. This seemed compatible with the requirements of a hand-held instrument in a single-seater airplane.

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The optical system is a 3× mirror-prism wide-field system (Model 5201) which was developed for night telescopes at the University of Rochester.[2] The triplet objective is placed

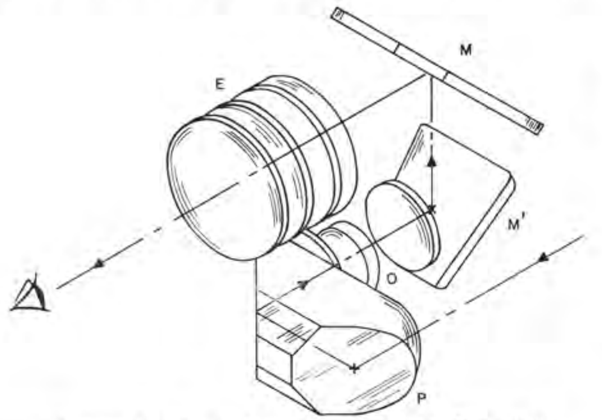


FIGURE 4. Optical system of 3× stadiameter.

between a conventional Porro prism and the two mirrors. This optical system, which is extremely compact, is shown schematically in Figure 4. The beam-splitting arrangement is

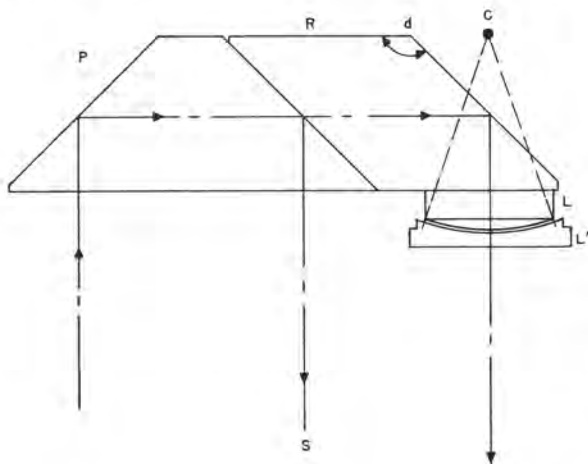


FIGURE 5. Beam splitter for 3× stadiameter.

shown in Figure 5. A glass rhomb R is cemented to one of the reflecting faces of the prism P, which is provided with a 50 per cent reflecting coat before cementing. The normal field of the telescope is unaltered except for the reduction in brightness of the beam S. The adjustable image is formed by light S', which has been reflected from the internal face of the rhomb and has been transmitted through the 50 per cent interface between the rhomb and prism. The deviation of the beam S' is produced by a variable angle prism, made up of a plano-convex lens L and a plano-concave lens L'. These have the same radii of curvature. The plano face of lens L is cemented to the rhomb. The concave lens L' is pivoted about the center of curvature of its curved face C so that the angle of the

FIGURE 6. Photograph of 3× stadiameter.

prism may be adjusted. The two curved lens surfaces are separated enough to permit motion without contact. Color is not serious up to about 50-mils separation of the images with 3× magnification. The field is 23 degrees, of which 18 degrees can be deviated and is available for stadiametric setting. The exit pupil is 7 mm in diameter, which is an advantage at dusk.

Rotation of the concave lens is controlled by an arm and screw, with a dial engraved in mils and a vernier reading to 0-1 mil. Zero adjustment is made by rotating the engraved head relative to the screw. Settings can be reproduced to 0.1 mil.

A photograph of the complete instrument is shown in Figure 6. It can be used conveniently with one hand, the second finger turning the knurled drum for setting while the rest of the

[redacted]

same hand supports and aims the instrument. Total weight is 40 ounces.

One unit was completed and will probably be kept at the University of Rochester, with the understanding that it will be available for Service testing at any time.

13.3 STADIAMETER FOR B-29 FIRE-CONTROL SYSTEM

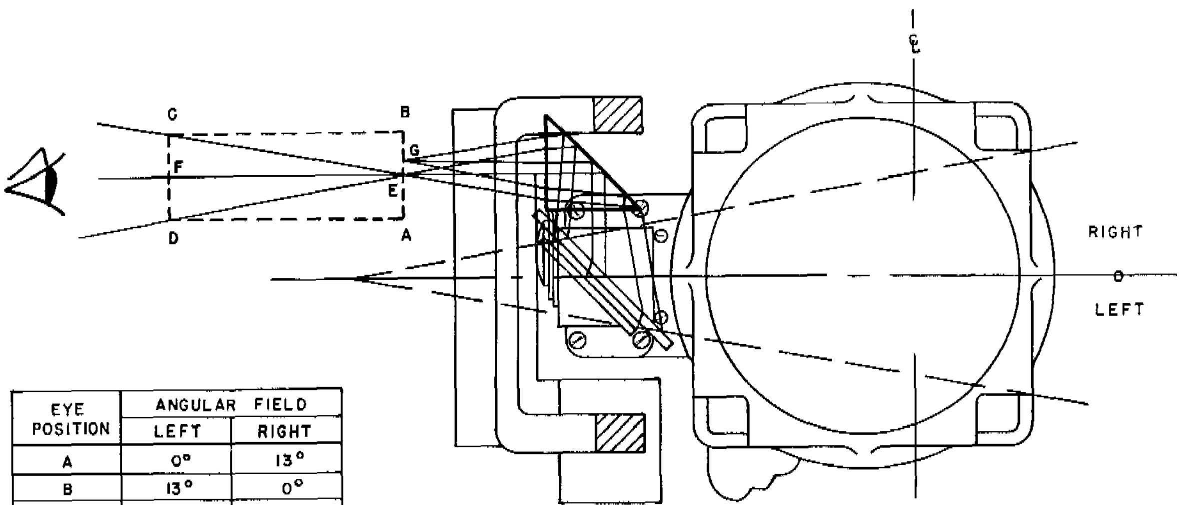
A quick means for estimating range with reasonable accuracy and feeding the result into the B-29 fire-control system is of the greatest importance for increasing the present accuracy of firing, particularly when rapidly approaching or receding targets are involved.

At the request of the Armament Laboratory at Wright Field, experiments were undertaken under Project AC-114 to determine whether a double-image stadiameter could be incorporated in the present pedestal sight. The University of Rochester contributed optical engineering and some special mirrors. The General Electric Company developed a prototype model for testing.

A stadiameter seemed likely to have definite advantages over the present ranging method in this application because it does not require the image to be located at any particular position in the field. All that is necessary is to have the double image included in the field of view so that the observer can bring the wing tips into coincidence. The adjustment can probably be made even if the double image is moving about in a moderately rapid and erratic fashion, under conditions which make the use of the common ranging dots difficult.

The design was based on the assumption that the simplest arrangement would be to mount a stadiametric device behind the present pedestal sight with a minimum of changes. The field should be restricted as little as possible, and eye relief should be adequate. It was desirable that the device be adapted for use with a camera to check performance of the gunner with the stadiameter. It seemed likely that unit power would be sufficient, and in any case the avoidance of lenses and an erecting system was a controlling consideration, at least in a preliminary model.

The optical system for the stadiameter is shown in Figure 7. Two mirrors are mounted, close together, in a vertical plane inclined 45 degrees to the line of sight. A 90-degree glass prism receives light reflected from these two



EYE POSITION	ANGULAR FIELD LEFT	ANGULAR FIELD RIGHT
A	0°	13°
B	13°	0°
C	10°	0°
D	0°	10°
E	10°	10°
F	5°	6°

FIGURE 7. Optical system of B-29 stadiameter.

mirrors and sends it to the eye of the observer. The first mirror has a coating on its first surface which reflects 35 per cent of the light to the prism and eye to provide a fixed image of the target. The light transmitted by the first mirror is reflected back through the same mirror by an aluminum coat on the front of the second mirror, and is turned by the prism to

FIGURE 8. Photograph of B-29 pedestal sight with stadiameter.

enter the eye in almost the same direction as the first beam. The second mirror can be rotated about a vertical axis through a mechanism linked to the range knob of the pedestal sight so as to control the apparent separation of the two images. It can also be adjusted to bring the two images into coincidence in the vertical direction. Figure 8 shows a photograph of the model mounted on the B-29 pedestal sight.

The basic design and the mirrors with appropriate high-efficiency coats were supplied to the General Electric Company. A prototype model was constructed just before the end of World War II, but information is not available regarding any tests that may have been made.

The design described above was intended merely to permit tests aimed at establishing the usefulness of a stadia ranging device. In a future model it would be very desirable to arrange for bilateral motion of the two images so that aiming could be done on the point of contact of their wings where attention must be concentrated for making the stadiametric setting.

13.4 RECOMMENDATION BY NDRC

The stadiametric ranging device for the B-29 fire-control system should be developed and tested, since it offers a promising solution of the requirements. Several alternative designs are possible. Unity power has marked advantages if it is adequate, since the entire field and also a large part of the present aperture can be used. Comparisons should be made with the present ranging equipment to determine the relative accuracy of the two methods, particularly in the case of fast approaches when it is difficult to hold the target steady at the center of the field. If the present stadiametric device appears to be promising, consideration should be given to developing a bilateral beam splitter, so that the gunner can aim at the point of contact between the two images of the target.

Chapter 14

ANTIOSCILLATION MOUNTS FOR OPTICAL INSTRUMENTS

By *Hobert W. French, Jr.*[a]

THE USE OF optical instruments in aircraft required suitable mounts to reduce the effects of vibration upon optical performance. Since no satisfactory mounts were available, their development was undertaken, first by the Institute of Optics, University of Rochester, and later by the Kodak Research Laboratories and the Technicolor Motion Picture Corporation, all under contracts with the NDRC. The mounts developed by the three groups differ in design and performance, but both laboratory and field tests demonstrate that all make possible a wider application of optical instruments in aircraft and under other conditions of severe vibration.

14.1 INTRODUCTION

Early in 1941, an investigation of aids to night vision was undertaken by NDRC, at the request of the Air Corps under Project AC-26. The Institute of Optics, University of Rochester, under Contract OEMsr-160, carried out extensive studies and developments in this field between 1941 and 1945, first under Section D-3 and later under Section 16.1 of NDRC. A conference with representatives of Section D-3 and certain British aircraft experts indicated a need for some device to bridge the gap between locating enemy aircraft at night with AI equipment and the actual sighting and firing of the guns of the pursuit planes. Preliminary studies of the problem led to the development of a wide-field 6× binocular night sight with illuminated reticle, for use by the pilot or gunner in the night interceptor planes. One serious obstacle to the practical use of this device, however, was the detrimental effect of plane vibration upon its optical performance. Since no effective mounting for an optical sight with this magnification was available, the Rochester group was faced with the necessity of developing a suitable one. After initial experiments with modifications of the rubber-in-shear type of shock mounting proved disappointing, the gimbal type of mount was conceived. Several successful mounts embodying this principle were built, both for binocular and monocular systems.[1, 2, 3]

To provide models better adapted to production and suitable for installation in specific aircraft, the Eastman Kodak Company Camera Works was requested by Section 16.1, NDRC (Contract OEMsr-1090) to redesign the Rochester gimbal mounts, both binocular and monocular.[4] This Eastman design was later incorporated in the Air Forces specifications when procurement was ordered.

In addition to the gimbal mount, two other types of antioscillation mounts were developed under Section 16.1, NDRC. The Kodak Research Laboratories entered into a contract (OEMsr-392) to improve the definition in aerial photography.[5] An important phase of this problem involved a suitable antivibration mount for aerial cameras. Experience gained with camera mounts led to a somewhat different solution of the vibration problem, but one which was equally applicable to the mounting of telescope systems.[6, 7, 8] Models of binocular mounts were built, both for aircraft and shipboard use. Confronted with the vibration problem in a periscopic binocular scanning device for aircraft use, the Technicolor Motion Picture Corporation evolved (Contract OEMsr-617) still another type of antivibration mounting.[9] This mounting also was applied to other types of optical systems, among them binoculars for aircraft and shipboard use.[10]

14.2 VIBRATIONS IN OPTICAL SYSTEMS

While vibration is generally harmful to any delicate instrument, in an optical instrument it

[a] Institute of Optics, University of Rochester, Rochester, New York. (At Argus, Incorporated, Ann Arbor, Michigan, since November 1, 1945.)

may not only cause mechanical damage, but it is almost certain to affect the optical performance adversely. Satisfactory antivibration or "shock mountings" had been developed for the protection of aircraft gyroscopic flight instruments prior to 1941,[11] but these mountings were not directly applicable to optical instruments. The problem of vibration in aerial photography was recognized in World War I, and some progress was made toward its solution at that time.[12] In the intervening years to 1941, however, very little more appeared to have been done on the aerial camera problem, and the mounting of other types of optical instruments in aircraft was apparently neglected entirely.

The purpose of the shock mountings used on flight instruments is to protect the delicate mechanism from the effects of the linear vibrational forces, thus preventing mechanical damage. While the protection of optical systems from mechanical damage by these forces may occasionally be necessary, this is not the primary problem. In viewing a distant object in a telescope system such as a pair of binoculars, a linear translation of the instrument as a whole in any direction causes no apparent motion of the distant object. This pure linear vibration of such a telescope, provided its component parts are sufficiently rigid so that no relative motion occurs, has no effect upon its optical performance. Furthermore, rotation of the telescope about its optic axis, or about any axis parallel to it, has no optical effect. Only components of rotation about axes lying in a plane perpendicular to the optic axis cause apparent motion of the distant object.

The magnitude of the effect of angular vibration depends upon the magnification of the optical system as well as upon the angular amplitude of the vibration. In an erect-image telescope, such as the ordinary binocular, the apparent angular motion of the distant object will be $(m - 1)$ times the angular motion of the optic axis, where m is the magnification. In an inverted image system the apparent motion will be $(m + 1)$ times the real motion. It is evident that erect-image systems are preferable to inverted-image systems when vibration is present. For example, a 3-power erect-image system is only affected half as much as a 3-power inverted-image system. Furthermore, unity-power erect-image systems are entirely unaffected by angular vibration, that is, they are invariant. Even for magnifications up to two or three power, very little effect is observed. Hence low-power erect-image systems do not generally need a special mounting to reduce angular vibration. For greater magnification, some type of mount is usually required, depending upon the optical performance demanded and the severity of the vibration.

In any type of antivibration mount, the vibration is never entirely eliminated; it is only reduced in amplitude until its effect is negligible or imperceptible. The measurement of effectiveness of a mount is the ratio of the amplitude of the instrument within the mount to the amplitude of the vibration impressed upon the mount. This ratio is called the "transmissibility" or "magnification factor." As has been mentioned, the optical effects of vibration are confined primarily to angular oscillations of the optic axis. A satisfactory mount must therefore reduce to negligible amplitude all angular vibrations about axes lying in any plane perpendicular to the optic axis. The amplitude may be considered negligible if the optical performance of the instrument is not perceptibly different in the presence of the vibration than it is in the complete absence of any vibration. It may sometimes be necessary to modify this rigorous requirement, and to consider a mount satisfactory if it permits an instrument to perform its useful function, even though some effects of vibration are still perceptible.

The antioscillation mount must not only reduce the effects of vibration in the optical system, it must also provide a satisfactory support and method of attachment so that the instrument is convenient to use. This problem is more difficult when the instrument is a gunsight, for then the direction of the optical axis must accurately maintain a fixed and known orientation with respect to the gun bore. In telescopic instruments for observation only, such accurate alignment is not necessary, but a smoothly operating swivel is essential for ease of use. An antioscillation mount will not function properly if any external forces act upon the

mounted instrument except through the filtering system. Hence, mounts must be provided with headrests or other devices which will properly position the observer's eyes without allowing him to touch the instrument. In some applications, the mounted system must also be shielded against buffeting by the wind.

14.3 TYPES OF ANTIOSCILLATION MOUNTS

In all of the mounts considered here, the optical instrument is, in effect, suspended at its center of gravity in such a way that it is free

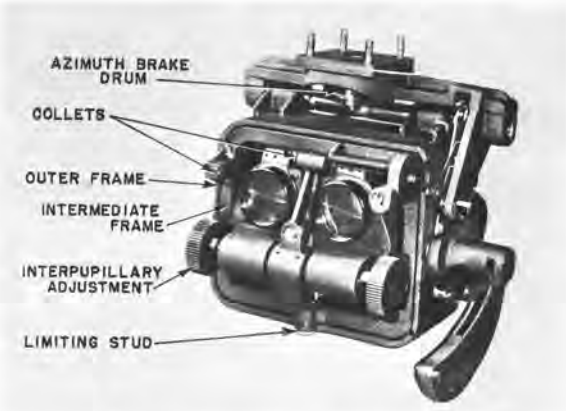


FIGURE 1. Eastman antioscillation-mounted binocular.

to rotate about it. If an instrument could be suspended exactly at its center of gravity, in perfectly frictionless bearings which permit complete rotational freedom about any axis, it would be impossible to exert any torque on the system through its support. The orientation of the instrument would remain fixed in space, regardless of any linear or angular motion of the support. Such a mounting is not possible, for perfectly frictionless bearings are unattainable, nor would it be desirable, for it is necessary to point the instrument by means of its support. Consequently, some type of restoring torque between the instrument and its mount is used to establish a mean or neutral angular relationship between the two. Because of this restoring torque, the instrument oscillates with a natural frequency determined by the magnitude of the torque and the moment of inertia of the system about its center of gravity. To limit the amplitude of these oscillations at and near the natural frequency, some type of damping is always necessary. These mounts differ from one another in the method of support at the center of gravity, in the form of the restoring torque, and in the type of damping.

14.3.1 Gimbal Mounts

In the mounts developed at Rochester and Eastman the optical system is supported in gimbals.[4, 13a] Unlike the pendulous gimbal mount

FIGURE 2. Eastman antioscillation binocular in P-61 aircraft.

commonly used for ships' compasses and chronometers, the center of gravity of the optical instrument is accurately located at the intersection of the gimbal axes, hence gravity exerts no torque on the system. The optical axis is perpendicular to the plane of the gimbal axes, permitting the former 2 degrees of rotational freedom. The gimbal axes are supported in precision self-aligning ball bearings, providing the maximum possible freedom of rotation. This mount is illustrated in Figure 1. In Figure 2 it is shown installed in the P-61 aircraft. Figure 3 shows a monocular mount, based on a similar design, for the gunner's station in the P-61.

The restoring torque and the damping are combined in a single air dashpot unit for each gimbal axis. The displacement of an elastic dia-

phragm, either of natural or synthetic rubber, provides the restoring torque. This diaphragm also forms one side of an air chamber. The displacement of the diaphragm forces the air in or out of the chamber through a small hole in the chamber wall. The length of this hole is large compared with its diameter, so that the air flow is essentially laminar. This type of air

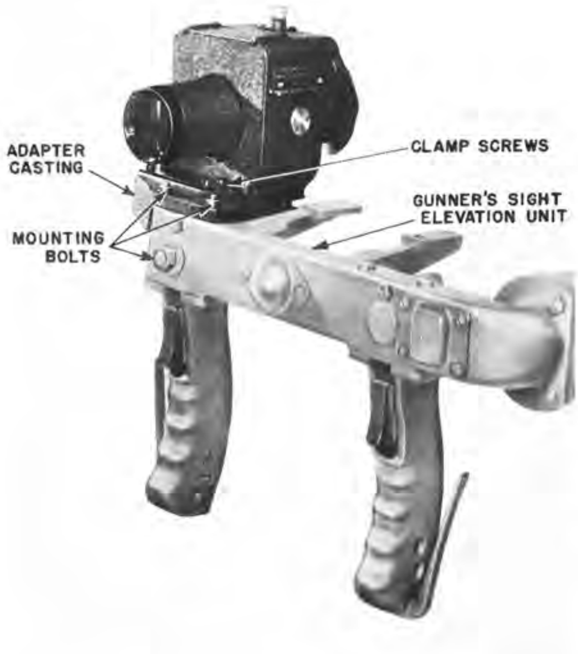


FIGURE 3. Eastman antioscillation-mounted monocular.

flow results in viscous damping, in which the resisting force is proportional to the velocity.

14.3.2 Ball-Cone and Rubber Shell Mounts

The mounts developed by Kodak Research Laboratories and Technicolor as applied to binoculars, support the instrument at its physical center of gravity. This is possible in a binocular, since the center of gravity falls outside the case, midway between the two halves, and below the hinge. Rotational freedom is obtained by a ball and socket type of universal joint, with the center of the ball located at the center of gravity of the binocular. This type of mount has three degrees of freedom of rotation about the center of gravity, whereas the gimbal mount permits only two.

While both the Kodak Research Laboratories

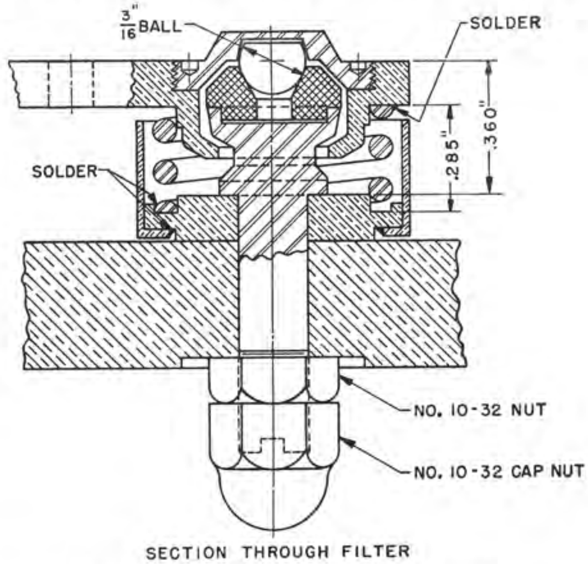


FIGURE 4. Kodak antioscillation unit.

and Technicolor mounts use frictional damping with this ball mount, they differ in the manner in which the damping is obtained, and in the

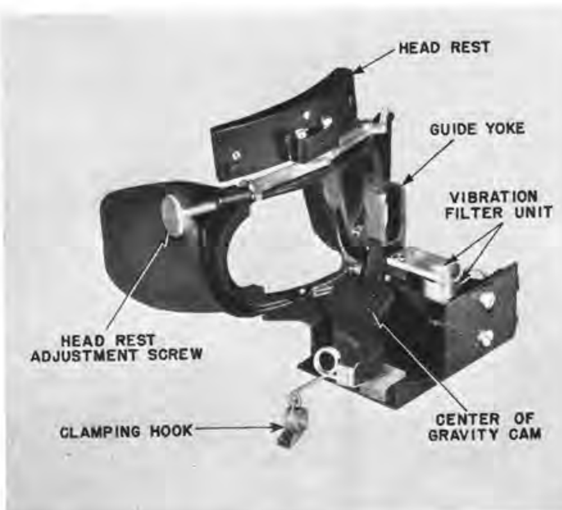


FIGURE 5. Kodak antioscillation mount without binocular.

method of applying the restoring torque. In the Kodak mount,[6, 7] the ball, attached to the binocular system, rests in a plastic conical seat

[redacted]

fixed on the top of the vertical supporting pillar (see Figure 4). Angular motion of the binocular, with resultant rotation of the ball in the plastic seat, is damped by the frictional forces between the ball and seat. The magnitude of the damping torque may be controlled by varying the diameter of the ball, or the taper of the cone, or by using different types of plastics having different coefficients of friction on steel. The restoring torque is applied by a helical metal spring concentric with the supporting

FIGURE 6. Kodak antioscillation mount with binocular.

pillar, and placed between it and the binocular unit. Since both ends of the spring are anchored, restoring torque is applied about any direction of rotation. The mount for aircraft and for shipboard use is illustrated in Figures 5, 6, and 7.

In the Technicolor mount,[10a] the ball is also attached to the binocular, but is held in a resilient rubber socket formed by two rubber washers compressed in a metal sphere composed of two hemispherical cups (see Figures 8 and 9). This metal sphere is firmly attached to the top of the vertical supporting pillar. Any rotation of the ball about its center sets up shearing forces in the rubber which apply the restoring torque. Thus the same restoring torque is applied about any axis of rotation. Frictional damping is obtained by a felt washer attached to the binocular part of the system and pressing against the outside of the top metal hemisphere.[10b] Since the latter is attached to the supporting pillar, angular motion of the instrument results in relative motion between the felt and the metal hemisphere, with frictional damping of the motion. In one version of the mount, the damping may be varied by changing the pressure of the felt washer upon the hemisphere. The restoring torque depends upon the elastic properties of the rubber and upon the physical dimensions of the rubber washers, the hemispheres, and the ball. Figures 10 and 11 show models of this mount for use in aircraft and on shipboard. All of the binocular mounts have interpupillary adjustments so designed as to preserve the location of the center of gravity with respect to the support point. In the University of Rochester and Technicolor designs this is accomplished by separating the two halves of the binocular and pivoting them about axes so located that the

FIGURE 7. Kodak antioscillation alidade mount.

shift in the center of gravity is a minimum. In the Kodak Research Laboratories' design, a unique cam arrangement permits the binoculars to be used without alteration. In all the models, headrests and eye guards attached to the supporting members position the observer's eyes with respect to the exit pupils of the instru-

ment, yet prevent contact or interference with the suspended instrument. In those Kodak Research Laboratories and Technicolor models designed for shipboard use, the entire instrument is enclosed in a shield to prevent transient oscillations from gusts of wind. This feature is not necessary for mounts used in enclosed airplane cockpits.

14.3.3 Comparison of Designs

Without any consideration, for the moment, of the performance of these different types, some comparison may be made of their general construction. Of those intended for use in aircraft, the Rochester and Eastman mounts are the largest and the heaviest. They also require more precision parts in their manufacture and hence are more expensive. The Kodak mount is the smallest, lightest, and simplest in construction. As pointed out above, it requires no modification of the standard type of binocular, and is undoubtedly the least expensive to build. Although embodying the same simple principle as the Kodak mount, the Technicolor design approaches the Rochester and Eastman units in bulk, weight, and complexity, although not in the precision required.

The gimbal principle, as used in the Rochester and Eastman mounts may be applied to monocular telescopes or other optical systems having the center of gravity located either inside or outside the body of the instrument,[3, 4] while the Kodak and Technicolor mounts are restricted in this respect. Because of the separate damper units about each gimbal axis, in the Rochester and Eastman mounts the restoring torque and damping can be independently controlled to give the same natural frequency about both axes, even though the moment of inertia is different about the two. Further, the gimbal system provides vibration isolation about only two axes—the two which affect optical performance. The third degree of freedom in the Kodak and Technicolor mounts adds almost nothing to the optical performance, and may cause greater linear motion and uncertainty in the position of the eye point. Finally, the performance of the balanced gimbal mount is completely inde-

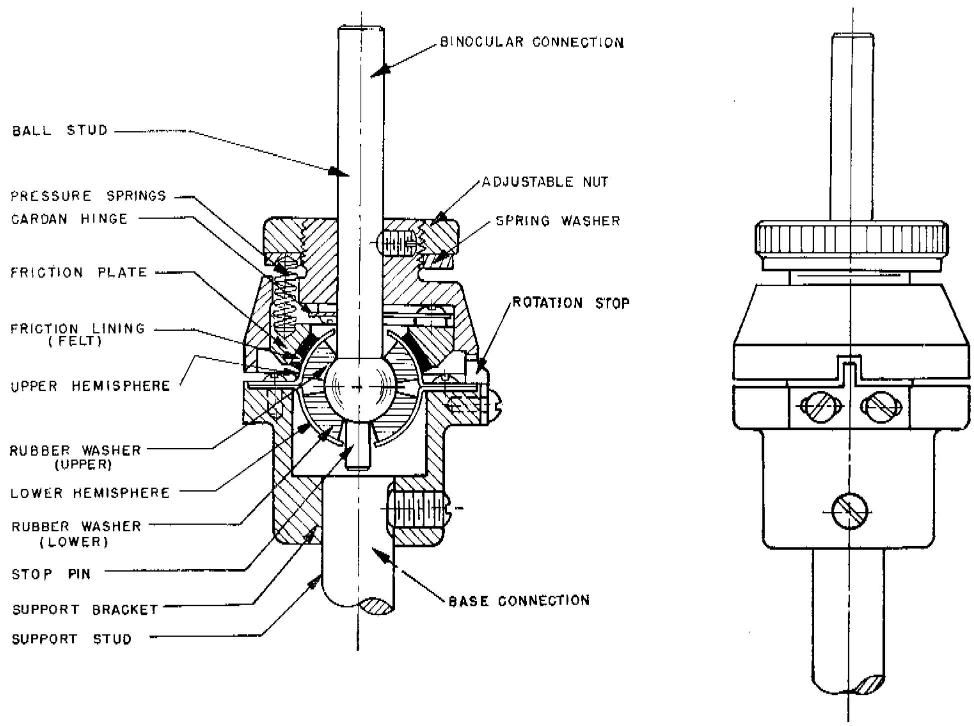


FIGURE 8. Technicolor antioscillation unit.

pendent of its orientation with respect to gravity, while the Kodak type of ball mount is limited to orientations within 60 degrees of its normal position, and the characteristics of the Technicolor mount are altered if the direction of gravity is changed materially. While these points are of concern in some applications, they are of little importance for most requirements.

FIGURE 9. Technicolor antioscillation unit disassembled.

By far the most important characteristic of an antioscillation mount is its vibration performance.

14.4 LABORATORY TESTING PROCEDURES

Since the results of any test can be properly evaluated only if the conditions under which the test is made are known, a careful consideration of the testing procedures is necessary. All three groups have conducted laboratory tests of their own type of mount. In addition, all three types of mount have been tested at the University of Rochester. Both the procedure and the results differ among the three groups.

One purpose of a laboratory test is to study the performance of a mount under known and controlled conditions of vibration. Only by such a study can optimum design and performance be obtained. A second and equally important objective of the laboratory test is to predict the performance of a mount under service conditions. To meet this requirement, the laboratory test should simulate service conditions as far as possible. Since the latter are not easily measured, and are known to vary widely, some compromise is obviously necessary.

14.4.1 Shake Tables

The shake table developed at the University of Rochester specifically for the testing of antioscillation mounts submits the mount simultaneously to the three components of linear vibration and to the two components of angular vibration which affect optical performance.[14] The amplitudes of these vibrations may be adjusted over a range greater than that observed in any service conditions. In any one test, however, these amplitudes are held constant, and the transmissibility is measured as a function of frequency. The frequency is varied from 50 to 2,000 vibrations per minute [vpm], a range which includes the fundamental frequencies of aircraft as well as marine engines. The frequency of linear and angular vibration are the

FIGURE 10. Technicolor aircraft antioscillation mount—vacuum cup mount.

same in any one test. Great care has been exercised in the design and construction of this shake table to insure that only one frequency at a time is present. While this condition obviously does not exist in actual service use, it is very important that it hold true in laboratory tests if an intelligent analysis of the performance characteristics is to be made. As a further precaution, the amplitudes of both the impressed and the resultant vibration are measured at each frequency. No assumptions are made as to the shake table having a constant amplitude over the frequency range. The performance is expressed in terms of the transmissibility or ratio of these two amplitudes, not in terms of the resultant amplitude alone. Although the impressed amplitude is held approximately constant over the entire range of frequencies, the transmissibility is relatively independent of amplitude over a wide range of amplitude, hence is a true characteristic of the mount, not of the mount and shake table combined. In order to insure that only one frequency at a time is present, and to provide a positive control of the amplitude at each frequency, the table is exceedingly rigid and is positively driven. Unlike shake tables which have a natural frequency of their own, this table provides an amplitude which is almost entirely independent of load or frequency. This permits a direct quantitative comparison between instruments of widely differing size, shape, and weight.

FIGURE 11. Technicolor shipboard antioscillation mount.

Although the results of a shake table test are contained in the final Kodak Research Laboratories report,[7] no description or discussion of the testing equipment or procedure is given. However, the shake table used in this test is described in an earlier report.[5a] This shake table provides only one angular component about a horizontal axis. If the center of gravity of the mounted system is displaced from this axis, one component of linear vibration is also obtained. In the test reported, however, it is stated that the axis of rotation is transverse through the center of gravity; hence no linear component is present.[7a] The test was made at constant impressed angular amplitude, and the resultant amplitude, rather than the transmissibility, is measured. The frequency range extends only to 500 vpm.

The shake table used by Technicolor was built for the testing of a periscope scanning device, and is described in a report on that equipment.[9a] Like the Kodak shake table, this unit provides only one component of angular vibration, and one linear component whose amplitude depends upon the distance between the center of gravity of the mount and the rotational axes of the shake table. By changing the orientation of the optical axis with respect to the axis of rotation of the table, all three angular components can be tested, but not simultaneously. Likewise, the three linear components can be checked, again, only one at a time. The frequency range of the table extends to 900 vpm.

14.4.2 Testing Methods

All three groups measure the angular amplitude of the optical system by the deviation of

[redacted]

a beam of light reflected from a small mirror rigidly attached to the system. In the Rochester tests, the deviation of the beam is obtained by measuring the linear displacement of a spot of light on a screen. Presumably the Kodak tests were similar. The Technicolor technique records the motion of the spot on a photographic film wrapped around a rotating drum. Although this requires considerably more time for a test, it has the advantage of providing a permanent record which can be studied in detail at leisure. The Rochester group on occasion photographed a distant object through the optical system of a binocular under test.[2] This method gives a very good record of the overall performance, but does not supply enough detailed information to permit a thorough analysis of the performance unless photographs are made at a large number of frequencies. The latter procedure was deemed too time consuming to be practical.

Since none of the groups has reported in any detail the actual performance of these testing devices, it is difficult to make any real evaluation of their relative merits. The unit was designed at the University of Rochester and many of the tests were carried out on it there. From this experience, it is possible to point out some of the more important factors to be considered in such an evaluation. First of all, it would seem very desirable to test a mount over the entire range of frequencies which it will encounter in service use. In aircraft, the normal operating engine speeds are around 1,800 rpm, although marine engines run considerably slower. For this reason, the Rochester shake-table frequency range extends from 50 to 2,000 vpm and tests are always made up to this frequency. The limit of the Kodak tests is 1,000 vpm, and the Technicolor 900 vpm. While it may be argued on theoretical grounds that for any mount having a natural frequency below these values the transmissibility at 2,000 vpm will always be lower than at 1,000 or 900 vpm, such is not necessarily the case. Secondary resonance points may arise from flexures in the mount. While it is the object of the designer to avoid such resonance points, it is exceedingly difficult, if not impossible, to predict whether they will be present or not. It is far safer to test the mount over the entire frequency range.

In the Rochester tests, the amplitudes of both the impressed and the resultant angular vibrations are measured at each frequency. This is done because experience has shown that, in spite of all precautions, the impressed amplitude varies somewhat with frequency due to flexures in the table structure. If great care is not exercised in both the design and workmanship of the table, the amplitude may vary several hundred per cent over the frequency range, the nature of this variation changing with different loads on the table. Depending on the phase relation between the impressed force and the flexure, the true amplitude may be either greater or less than expected. The Kodak data is given in terms of resultant amplitude, with a single value of impressed amplitude. While it is stated that this impressed amplitude is constant, either the tolerance on this "constancy" should be given or the data should be in terms of the transmissibility ratio. The Technicolor data is likewise reported as resultant angular amplitude, with the photographic records showing the impressed amplitude at only one frequency. The occurrence of nonsinusoidal wave forms is mentioned and attributed to vibrations in the bed of the testing equipment.[10c] This would seem to emphasize the necessity for measuring impressed amplitude at each frequency.

While a test which simultaneously impresses the components of linear vibration and the two important angular components more closely approaches actual conditions of use, its primary advantage is probably that of convenience. There is, however, a possibility of interaction between the two angular components which might lead to a different result if each component were tested separately. Both theoretical considerations and experience indicate that this possibility is slight in a well-behaved mount. As has been pointed out in the Kodak Research Laboratory report,[8] if linear and angular vibrations are impressed simultaneously on a system which is not completely balanced, the phase relation between the two must be taken into consideration. In such a case, it is better to test the effects of linear and angular vibrations separately, and to take the pessimistic attitude by adding the resultants. In practice,

however, the system should be so well balanced that only a negligible amount of linear-angular coupling exists. The primary reason for testing with linear vibrations present is to determine whether the linear accelerations, through flexure of the inner components, impair the effectiveness of the mount. Proper balance may be determined easily and accurately by a static test, but the effects of flexures require a dynamic test.

14.5 LABORATORY PERFORMANCE

The generally accepted method of expressing the shake-table performance of an antioscillation mount is a plot of transmissibility, or ratio of resultant to impressed angular amplitude, against frequency of impressed vibration. Resultant angular amplitude may be used in place of transmissibility provided the impressed amplitude is known to be constant over the entire frequency range. It is also customary to resolve the angular vibration into components about a horizontal axis and a vertical axis, both perpendicular to the optical axis, and to give plots of the transmissibility for each component. The component about an axis parallel to the optical axis may also be measured, but is usually omitted since it does not affect optical performance. In the event that linear vibration is also present, the amplitudes of the three linear components at the center of gravity should also be given.

14.5.1 Tests Reported

A Rochester report gives the performance curve of a Type II-c binocular antioscillation mount as a graph up to 700 vpm with the value of transmissibility at 1,600 vpm and the maximum value between 750 and 2,000 vpm.[2] Photographs of a distant building taken through the binoculars vibrating at 1,600 vpm, with the mount in operation and clamped, and also without vibration, are included in the same report. In a later report,[14a] the results of a number of tests on Type II-b mounts are given in a single graph for frequencies up to 2,000 vpm. The standardized conditions under which these tests were run are also given.

A Kodak report gives the results of a single test on a binocular mount, for one component of angular vibration, with no linear component at the center of gravity.[7a] The frequency range is 0 to 500 vpm.

A Technicolor report[10] contains a considerable number of graphs, showing the performance of their units under a variety of conditions. These curves show the effect of interpupillary adjustment, the effect of rotation only and of rotation plus translation, changes in restoring force, and different types of supports. The photographic records from which the graphs are drawn are also included in some cases. The highest frequencies reported in these tests range between 750 and 1,000 vpm. Except for this limitation on frequency range, the data is much more comprehensive than that of the other two groups. In addition to the above tests, all three types of mounts were tested at Rochester under the standardized conditions established for the Rochester mounts.[14] These tests cover the gimbal mounts built at Rochester; three gimbal mounts of the Eastman Kodak Camera Works production design, one each made by the Camera Works, the Houston Company, and the Robinson-Houchin Company;[b] and a monocular unit made by the Camera Works. Of the ball-type mounts, three tests of the Technicolor shipboard model and one of the Kodak Research Laboratories' unit are reported.

14.5.2 Evaluation of Tests

Any comparison of the various types of mounts which is based upon the above information must necessarily be limited, since this information is far from sufficient for a truly complete analysis. The results of many tests on Rochester mounts have not been reported because of obvious limitations of time and space. The same is undoubtedly the case for both the Kodak and Technicolor tests, although the latter are reported in the most detail. Furthermore, the primary objective of each group has been to develop its own type of mount;

[b] These units were the first production models built for the Army Air Forces for installation in P-61 night fighters.

hence the tests have been made with this in mind rather than any comparison between types. Only the tests at the University of Rochester of the various types provide any direct basis for comparison, and these were limited to a single test on one type, and three tests on the other.

The performance of any antioscillation mount should be judged primarily in terms of its effectiveness in reducing the harmful effects of vibration upon optical performance. As we have pointed out earlier, only angular vibrations of the optical system about an axis perpendicular to the optical axis are harmful, but it must be remembered that such vibrations may result from impressed vibrations which are either linear or angular, or a combination of both. In any of these mounts, the transmissibility, which is a quantitative measure of effectiveness, varies greatly with the frequency of the impressed vibration. Hence any statement of effectiveness must include this frequency. In general, the higher the impressed frequency above the natural or resonance frequency of the mount, the lower the transmissibility and the more effective the mount. For this reason, it is desirable for the mount to have as low a natural frequency as possible. Unfortunately, practical design considerations and factors concerned with service use impose a lower limit. The effectiveness of the mount should be evaluated in terms of its transmissibility at that frequency to which it will be subjected in actual use. In aircraft, the predominant vibration arises from the engines, which have a fundamental frequency of 1,600 to 2,000 vpm. In mounts intended for aircraft use, the transmissibility should then be compared at these frequencies. Since neither the Kodak nor Technicolor reports contain any data at these frequencies, the sole basis for comparison is the Rochester tests.[14] In this range, the gimbal mounts built at the University of Rochester have transmissibilities between 1 and 5 per cent,[c] the latter value being on the upper limit of acceptable performance. Two of the three Eastman production design gimbal mounts also have transmissibilities of about 5 per cent in this range.[14b] A Technicolor shipboard mount, tested at three values of the damping adjustment, showed transmissibilities of 5 per cent or less for low values of damping, but values of 10 to 15 per cent for moderate and heavy damping.[14c] The single test on the Kodak mount gave values between 5 and 7 per cent.[14d]

The engine vibration is the predominant vibration in aircraft, but by no means the only one. There are, of course, higher harmonics of the fundamental engine frequency, from the multiple cylinders, multibladed propellers, and natural resonances in the plane structure. The amplitude of these higher harmonics is usually much smaller than that of the fundamental, and the effectiveness of the mounts is much greater at higher frequencies; hence higher harmonics may be neglected. Among the lower frequencies, which cannot be neglected, are vibrations arising from flutter in the air foil, beats between the engines in multiengine planes, and most important, the motion of the plane as a whole in pitch, yaw, and roll. The frequency of these latter motions is apt to be very close to the resonant frequency of the mounts. An inspection of the transmissibility curves will show that none of the mounts is effective at or near its resonance frequency, for the transmissibility is greater than 100 per cent. Since 100 per cent represents the performance which would be obtained if no mount at all were used, antioscillation mounts are actually harmful in this frequency range. For this reason, it is necessary to provide considerable damping in a mount, so that oscillations excited by the motion of the plane will not build up in amplitude, but will die out quickly. The second point at which mounts should be compared is therefore at the resonant frequency.

As a result of experience gained in flight tests, the Rochester mounts are provided with sufficient damping so that the maximum transmissibility at resonance does not exceed 120 per cent. Both the tests at Kodak[7a] and at Rochester[14d] show that the Kodak mount has a very low transmissibility at resonance, between 120 and 140 per cent. The Technicolor mounts have an adjustment which permits a wide range of damping. In their report,[10] values all the way

[c] Transmissibility may be expressed either as a percentage or as a decimal fraction. Technicolor reports use the former, and University of Rochester reports the latter.

from 130 to 270 per cent are shown. In the Rochester tests on the Technicolor unit, the damping was varied to give resonance transmissibilities from 120 per cent to well above 300 per cent. It was only at low values of damping that the transmissibility in the 1,600 to 2,000 vpm range was reduced to 5 per cent.

There are both theoretical reasons and experimental evidence to show that low damping gives the best performance at high frequencies. The selection of the optimum damping is therefore a compromise between the highest transmissibility which can be tolerated at resonance, and the best performance at the predominant frequency, which is 1,600 to 2,000 vpm in aircraft. Obviously, a low transmissibility at both points is highly desirable, but theoretical considerations discussed later set a lower limit which is dependent upon damping.

14.6 BORESIGHTING

Although the primary aim of an antioscillation mount is to reduce the effect of vibration on optical performance, the use of mounts for optical gunsights introduces a further requirement. In this application, the optical axis of the instrument, or the "line of sight," must accurately maintain an angular relationship with the line of fire of the gun, that is, the optical sight must "boresight" accurately. In aerial gunnery, the boresighting must not have an error greater than about 1 or 2 mils (thousandths of a radian).

This boresighting accuracy, at least in aircraft, is only required under conditions of vibration, since the guns are used only when the plane is in flight. The term "dynamic boresighting" has been used to designate the boresighting performance under conditions of vibration, while "static boresighting" refers to the performance in the absence of vibration. It might appear, at first glance, that static boresighting is unimportant in service use, but such is not the case. The boresighting is customarily checked before each operational flight, or after any servicing of the guns. Since a convenient and accurate check of boresighting can only be made with the plane on the ground, the normal flight conditions of vibration are not present. In fact, it is difficult to make such a check with the plane motors revolving at cruising speed. It is therefore desirable that the boresighting be done in the absence of vibration, and this requires that both the static and dynamic boresighting be accurate.

Since the Rochester mounts were initially designed for aircraft gunsight use, the problem of boresighting was given important consideration, along with the vibration performance itself. For this reason, the use of antifriction bearings and viscous damping was adhered to in all of the mounts. As a result, the ball-bearing gimbal mounts meet both the static and dynamic boresighting requirements. The ball-type mounts, employing dry frictional damping, are not as satisfactory in this respect. While the dynamic boresighting of these mounts may be sufficiently accurate, as in the Kodak mount tested at the University of Rochester,[14d] the static boresighting is inherently inaccurate. In the Technicolor mount tested at Rochester, neither the static nor dynamic boresighting was satisfactory for gunsight applications.[14e] It should be remembered, however, that imperfections in boresighting do not necessarily indicate poor vibrational performance. For applications not requiring accurate maintenance of the line of sight, such as detection and recognition, the ball mount with dry friction damping is entirely satisfactory.

14.7 FIELD PERFORMANCE

While the ultimate criterion of the usefulness of an antioscillation mount is its performance under service conditions in an aircraft or on shipboard, the difficulties in conducting such tests have been formidable. During World War II, both equipment and personnel at the various Army and Navy bases in this country were overburdened, hence the time and facilities which could be allotted to the testing of antioscillation mounts were limited. The results of such tests were consequently confined to the qualitative observations of military and civilian personnel, the former, in most instances, entirely new to the problem, and the latter unavoidably biased by long familiarity with it. Nevertheless, these qualitative tests were val-

uable in guiding the development of the mounts and in demonstrating their practicability.

Although the Rochester mounts were subjected to a variety of tests, both by the Army Air Forces and the Navy, only the earlier tests have been reported in any detail.[13] The results of the several months of testing and operational use in night-fighter training at the Orlando Air Base has not been reported by the contractor. This program not only gave valuable aid to the improvement of mounts, but clearly proved their tactical value. As a result of these tests, the Air Forces issued procurement orders for these mounts for use in P-61 night fighters.

On other occasions, Rochester mounts were tested in Navy patrol planes of various types, for sea search and surface-vessel recognition and for submarine detection at night. Although the tactical effectiveness seemed to be less clearly shown in these applications, the vibration performance of the mounts was in every case satisfactory. Only one shipboard test was reported,[13b] and the vibration to which the instrument was subjected was so slight that no far-reaching conclusions could be made.

Both aircraft and shipboard tests of the Technicolor mounts have been reported.[10] The aircraft test, in a PBY patrol bomber, gave valuable information as to the optimum damping, and indicated the need for certain minor mechanical modifications, but the vibration performance was satisfactory. The shipboard tests on a destroyer yielded further information on the type of vibration encountered in surface vessels and on the optimum damping for these conditions. Again the vibration performance of the antioscillation mount was a great improvement over that of rigid mounts or hand-held instruments.

The Kodak mount was tested on a destroyer with encouraging results, and the results of these tests were the basis for redesigning the alidade mount to provide greater stiffness and filtering for linear vibration.

14.8 VISCOUS VERSUS FRICTIONAL DAMPING

The relative merits of viscous and frictional damping have been subject to some difference of opinion among the groups working on the problem of antioscillation mounts. The Rochester group upholds the advantages of viscous damping, while the Kodak and Technicolor groups adhere to frictional damping. These differences include both theoretical performance and practical applications.

Viscous damping exerts a resisting force proportional to the velocity of the system being damped, while frictional damping exerts a nearly constant force, almost independent of the velocity. Theoretically the two types of damping give rise to different characteristic curves of transmissibility versus frequency. An adequate discussion of the theory of damping would require more space than is available in this report, hence only an outline of the arguments and conclusions can be given here.

14.8.1 The Function of Damping

In the application of the theory of vibration isolation to antioscillation mounts for the optical systems, the only case which need be considered is that in which the source of vibration is external to the system, and affects it through a harmonic motion of the supports. If the supports are rigid, the system vibrates with the same amplitude as its surroundings, and there is no vibration isolation. If the supports are resilient, the amplitude of the system may be either greater or less than the amplitude of the surroundings, depending upon the ratio of the natural frequency of the system to the frequency of the surrounding or impressed vibration. In either case, the motion of the system is the result of a harmonic force transmitted through the resilient supports and dampers. The theoretical transmissibility versus relative frequency of a typical antioscillation mounting is shown in Figure 12.[d] The transmissibility is the ratio of the amplitude of the suspended system to that of its surroundings, while the relative frequency is the ratio of the frequency of the surroundings vibration to the natural frequency of the mount.

Curve A, Figure 12, represents a system

[d] The theoretical derivation of these curves may be found in the literature.[15a]

without damping. At very low relative frequencies, where the natural frequency of the mount is high compared with the impressed frequency, the transmissibility is unity. As the impressed frequency approaches the natural frequency, the transmissibility increases rapidly, becoming infinite at unity relative frequency, the resonant point of the system. As the relative frequency increases above the resonant point, the transmissibility decreases, passing through unity at a vibration frequency of 1.41 ($\sqrt{2}$) and becoming less than unity for still higher frequencies. In the relative frequency range from zero to 1.41, the antioscillation mount is

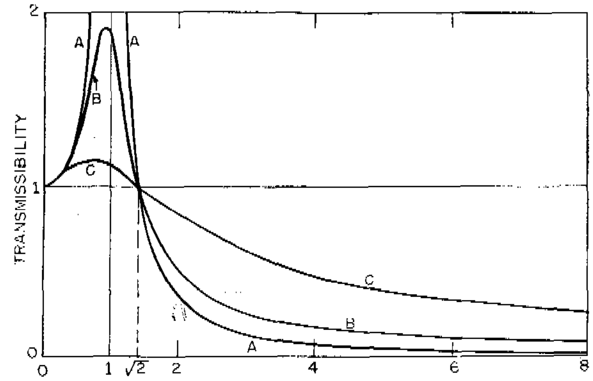


FIGURE 12. Transmissibility versus relative frequency. Curve A, zero damping, curve B, medium viscous damping, and curve C, heavy viscous damping.

valueless, and, in fact, even harmful, for the transmissibility is greater than unity. At or near the resonant point, an undamped mount may cause real damage to the suspended system. Only for the relative frequency range above 1.41 is the mount useful in reducing the effects of vibration.

Curve B shows the transmissibility of a system with a moderate amount of viscous damping. For relative frequencies below 1.41, the effect of damping is seen to be beneficial, since the transmissibility no longer goes to infinity at the resonant point, but is limited to a rather moderate value. Nevertheless, the transmissibility is greater than unity over this range. Hence, the mount is still ineffective, although less harmful, with damping than it was without. In the range above 1.41, where the undamped mount was effective, the damped mount is still effective, but less so, since the transmissibility is everywhere greater. Curve C, for greater viscous damping, shows a further decrease in transmissibility from zero to 1.41, and a further increase above that value.

From these curves, we may conclude that damping is in the nature of a necessary evil. Some damping is required to keep the transmissibility at and near resonance within reasonable limits. The minimum damping which will accomplish this is the optimum amount, for damping decreases the effectiveness of the mount in the range above resonance. Curve A for zero damping gives the theoretical minimum transmissibility for relative frequencies above 1.41, thus representing the theoretical optimum performance in the useful range.

14.8.2 Theoretical Comparison

Since damping is necessary in the range below 1.41, but undesirable above that value, the question naturally arises as to whether some other type of damping than viscous might be more suitable. Any other type must still limit the transmissibility at or near resonance, but should increase the transmissibility at high frequencies less than does viscous damping. The proponents of dry friction, or coulomb damping, claim just this property.[5c, 8a, 9b]

The theory of vibration isolation for systems with viscous damping has been well developed by a number of workers in the field of vibration, in particular, Timoshenko[16] and Den Hartog.[15] The rigorous treatment of problems in forced vibration for other forms of damping is complicated, but approximate solutions are available which are sufficiently accurate for most practical applications.[15, 16] A brief consideration of the energy relationships involved will give an indication of the general behavior of such systems under different types of damping.

If one considers a vibrating system at resonance, the energy input per cycle is $\pi P_0 \chi_0$, where P_0 is the harmonic exciting force, and χ_0 the amplitude of the motion. Plotting energy

per cycle against amplitude, χ_0, in Figure 13, we may represent the energy input per cycle by the straight line OA. The energy dissipated per cycle by viscous damping is $\pi C\omega\chi_0^2$, where C is the damping coefficient and ω the angular frequency. The energy dissipated in viscous damping may be represented by the parabola OB. It is evident that the parabola must intersect OA at the origin and one other point. At this latter point, the energy dissipated per cycle just

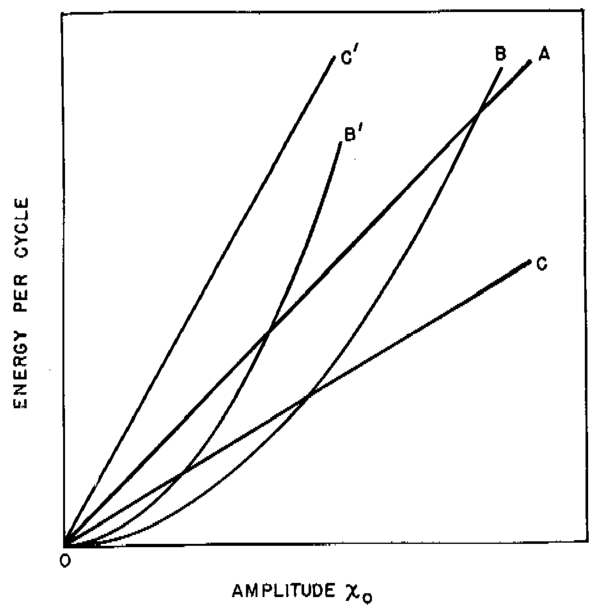


FIGURE 13. Energy per cycle versus amplitude. OA represents energy input, OB and OB' energy dissipated in two values of viscous damping, OC and OC' energy dissipated in two values of frictional damping.

equals the energy input, and the system is in equilibrium. The amplitude at which the system is in equilibrium is obviously the resonant amplitude for that particular value of the damping coefficient.

A different value of damping coefficient may be represented by another parabola OB' which intersects OA at another value of amplitude. Thus the amplitude at resonance depends upon the value of the damping coefficient. The important point, however, is that for all values of damping coefficient, the parabola representing energy dissipated always intersects the straight line representing energy input at a point corresponding to a finite amplitude. There is always a finite amplitude at which the system is in equilibrium.

In the case of frictional damping, the energy dissipated per cycle is $4F\chi_0$, where F is the damping force, which is independent of velocity. The energy dissipated here will be represented by a straight line such as OC or OC', depending upon the magnitude of the damping force. If the frictional damping force is small, as it is for OC, the energy dissipated is less than the energy input for all amplitudes. This is illustrated by the fact that OC has a smaller slope than OA. Under this condition, no equilibrium amplitude is reached, for the energy flowing into the system continually exceeds that dissipated, and the amplitude becomes infinite. If the frictional damping force is large, represented by OC', the energy dissipated per cycle by the damping exceeds the energy input, and true sinusoidal oscillations do not occur. An exact solution of the equation of motion in this case is not possible, but an approximate solution has been worked out by Den Hartog.[15b] It is too complicated to be included in this discussion, but the results are given in the literature. The important point here is that only for large values of frictional damping is the amplitude finite at resonance.

Thus from the above theoretical considerations, we may conclude that below a certain critical value, frictional damping fails completely in its most important function, that of controlling the amplitude at or near resonance. Furthermore, this critical value is not a constant of the system but depends upon the energy input per cycle, which is $\pi P_0\chi_0$, as explained above. Hence, for one set of conditions, in which the impressed force is small, the frictional damping in a system may be sufficient to prevent the amplitude from becoming infinite. In this same system, however, a small increase in the magnitude of the impressed force may raise the energy input per cycle above the energy dissipated by the frictional force, and the amplitude will become infinite. While viscous damping will always limit the amplitude at resonance, frictional damping may or may not, depending upon the external conditions.

In the region in which the mount is effective,

[redacted]

we have stated that damping is always detrimental, as shown by the curves in Figure 12. This statement applies both to viscous and to frictional damping, but the problem is to determine which is less harmful. While it is possible to calculate the performance of a system with viscous damping under any set of conditions from the constants of the system alone, such a generalized calculation unfortunately is not possible for a system with frictional damping. In the latter case, specific external conditions must be assumed, hence no generalized theoretical comparison between the systems themselves may be made. Only general trends may be considered.

The exponents of viscous damping have argued that it possesses an important advantage over frictional damping from the viewpoint of filtering action at high frequencies.[5c, 8a, 9b] They reason that the rate of energy absorption by a damper is equal to the product of force and velocity. Since the force for a viscous damper is proportional to the velocity, it follows that the rate of energy absorption is proportional to the square of the velocity. For the dry-friction type of damper, the force is substantially independent of velocity, hence the rate of energy absorption is proportional to the first power of the velocity. Up to this point, the two groups are in agreement. The proponents of frictional damping go on to compare the two types of damping at low and at high frequencies, making the comparison at the same amplitude, and conclude that the frictional damper absorbs relatively less energy at high frequencies, hence is more favorable. This comparison seems to us to avoid the real issue. The question is not which damping absorbs the more energy at the same amplitude. The real question is what is the resultant amplitude for each type of damping under equal impressed forces. The absorption of energy by a damper is a desirable, not an undesirable characteristic, hence on this line of reasoning we should conclude that viscous damping is better than dry-friction. The detrimental action of a damper arises from its ability to transmit part of the externally applied force through to the suspended system. The net effect of damping is the resultant of these two opposing actions.

14.8.3 Experimental Comparison

Since it is necessary to calculate the performance with frictional damping by laborious methods for each specific set of conditions in order to compare it with viscous damping performance, it would seem both easier and more conclusive to resort to direct experimental comparison. For viscous damping in the Rochester gimbal mounts, the theoretical and experimental performance are in close agreement. In one example reported,[1] the experimental values for a Type II-c antioscillation mount correspond very closely to the theoretical transmissibility for a system with a damping coefficient of 0.3 critical. It should be noted that this value of damping corresponds to a maximum transmissibility at resonance of about two. Similar experimental performance is also reported for a group of tests on Type II-b mounts.[14a]

The few available shake-table tests of mounts with frictional damping show a considerable range of performance. The Technicolor mount tested at the University of Rochester was provided with adjustable damping, thus permitting some investigation of the effects of variation in this characteristic.[14c] For low amounts of damping, the transmissibility at resonance was very high. The amplitude was, of course, limited by the mechanical stops, but from the theoretical standpoint it might be considered infinite. At frequencies from 10 to 20 times the resonant frequency, the transmissibility was very low, approaching the theoretical value for zero damping. A second test, with a moderate amount of damping, showed a transmissibility at resonance of about 2.6 for one component and 1.5 for the other. At the higher frequencies, the transmissibility was appreciably higher. The third test, with relatively heavy damping, gave transmissibilities at resonance between 1.2 and 1.3, and a still greater increase at the higher frequencies. This performance is, at least qualitatively, in agreement with the theoretical predictions for frictional damping considered above.

The single Rochester test of the Kodak mount,[14d] on the other hand, gave somewhat different results. In this test, the damping was sufficiently high to limit the transmissibility at

resonance to about 1.2. This corresponds to a high value of viscous damping. Yet the transmissibility at higher frequencies was relatively low, corresponding to only a moderate amount of viscous damping.

14.8.4 Conclusions

The limited theoretical consideration of the problem and the meager experimental results made it difficult to draw any decisive conclusions regarding the relative merits of viscous and frictional damping. The theory seems to favor the former, but the experimental test on the Kodak mount cannot be passed over lightly. While the performance of the Kodak mount does not substantiate the claim that frictional damping is superior to viscous damping in competitive tests,[7b] it does prove that the transmissibility at resonance may not only be finite, but even lower than is normally the case with viscous damping, while the transmissibility at higher frequencies may be as low as a moderately damped viscous system. It should be noted, however, that the transmissibility in the operating range (1,600 to 2,000 vpm) is on the upper limit of acceptability for gimbal mounts.[14a] It is not as low as the average for the latter, and is several times as large as that of the Type II-c reported.[1] In the matter of boresighting accuracy, the Kodak claims are also not borne out. The dynamic boresighting was not quite within limits established as acceptable for gimbal mounts at Rochester.

Other claims for the Kodak mount are certainly justified. It possesses simplicity of construction, uses standard binoculars without modification, is compact and light in weight, and would seem to require a minimum of maintenance. In all these respects, its superiority to the gimbal mount must be conceded. Only where the best possible vibration performance is required, or in gunsight applications where accurate boresighting is essential, does the more elaborate gimbal mount have a real advantage which may justify its increased complexity.

14.9 DISCUSSION

The experience gained with the various antioscillation mounts, both in the laboratory and under actual service conditions, is ample proof that there are definite advantages in their use. Undoubtedly, considerable improvement in both design and performance can be made. The wartime pressure under which these developments were made does not lead to the ultimate in results. Both from the academic and the practical viewpoint, much value would be derived from further investigation of the relative advantages of viscous versus frictional damping, particularly based on practical tests under service conditions. Certainly improvements in both types of damping should be expected.

The application of antioscillation mounts is an urgent problem. The basic principles have been firmly established and successfully reduced to practice. A search for additional profitable applications should be undertaken. During World War II, it was exceedingly difficult to carry out thorough and unhurried field tests of this equipment. Some of those leads which looked promising, but which had to be abandoned for more urgent problems, should now be followed up. A careful study of the requirements of each application would probably result in a considerable modification of the design and performance characteristics of the present mounts. Obviously, one design cannot be optimum for all problems. A further investigation of the theory and general performance, combined with the adaptation to specific problems, should provide more incentive and yield more beneficial results than a laboratory research investigation alone.

14.10 RECOMMENDATIONS BY NDRC

1. The gimbal mounts (University of Rochester and Eastman), the ball-and-cone mount (Eastman), and the rubber-shell mount (Technicolor) should all be tested more completely in the laboratory, in aircraft, and on shipboard to determine the extent to which each is applicable to existing needs. The effectiveness of the base filtering unit in the Technicolor mount should be determined. Boresighting accuracy should be measured, both statically and dynamically, for each mount.

2. Further theoretical and experimental studies are desirable, to settle the relative merits of dry-friction and viscous damping.

3. Antioscillation mounts should be developed for a number of special applications, such as high-power telescopes for use in aircraft and on ships, and for gun cameras.

4. Comparisons should be made between the performance of binoculars in the most effective antioscillation mount with hand-held standard binoculars and with binoculars to which weighted arms have been added, with elbow rests and with provision for relieving the observer from carrying the extra weight involved (see Chapter 5). These tests should be made both in aircraft and on shipboard. A comparison should also be made with the British support for the elbows, which is carried on the thighs.

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Chapter 15

PHOTOTHEODOLITES

By *Leo Goldberg*[a]

15.1 INTRODUCTION

15.1.1 Origin of Problem

AT A CONFERENCE held at Fort Monroe on December 3, 1941, representatives of the Ordnance Department, Aberdeen Proving Grounds, Signal Corps, Coast Artillery Board, and Naval Proving Ground agreed that there was a need for the development of a pair of phototheodolites capable of measuring the position of a target in space with all possible accuracy. NDRC was asked to undertake a comprehensive study of the problem. A preliminary investigation was begun by Section D3 (Instruments) at the request of Section D2 (Fire Control). On March 1, 1942, project OD-48 was established to cover development of these instruments. When NDRC was reorganized in December 1942, this project was transferred to Section 16.1. The Services requested that plans be made to modify a pair of existing phototheodolites, if sufficient accuracy could be obtained. Otherwise the design and construction of two entirely new instruments was recommended. The study of existing phototheodolites as well as the design and construction of the new instruments was carried out by the Eastman Kodak Company [EKC] under Contract OEMsr-503.

15.1.2 Applications

The most important applications for precision phototheodolites envisaged by the various branches of the Services were:

1. Testing of heightfinders.
2. Testing of performance of operators of heightfinders and rangefinders.
3. Construction of range and fuze tables for use with antiaircraft guns.
4. Construction of bombing tables.
5. Recording of motion of rockets and other special projectiles.
6. Recording of aircraft motions.
7. Testing the overall accuracy of fire-control equipment.

15.1.3 Specifications

In order to meet the recommendations of the Services, the following specifications were indicated.

OPTICAL FEATURES

1. Cameras with interchangeable optical systems, having focal lengths of 12, 24, and 48 in., and relative apertures of $f/5$ at least, for night photography.
2. Exposures on 35-mm film, each frame to contain, in addition to the photograph, the film number, azimuth and altitude angles, time of exposure, and an image of a fixed reference reticle.
3. Exposures to be made at intervals of from 1 to 10 sec, or at motion-picture rates, as desired.

TRACKING FEATURES

1. Design to provide for two-man aided tracking.
2. Tracking telescopes to be 8× with 8-degree field.

SYNCHRONIZATION

1. When a target is being tracked by two stations, the recording of altitude and azimuth angles is to be synchronized to within 0.001 sec.

MECHANICAL FEATURES

1. Overall accuracy of angle measurement to be 0.1 mil.
2. Automatic correction for refraction of atmosphere, if practical.
3. Instrument to be equipped with an accurate bubble level.

[a] McMath-Hulbert Observatory of the University of Michigan, Lake Angelus, Pontiac, Michigan.

15.2 STUDIES OF EXISTING PHOTOTHEODOLITES

15.2.1 Akeley Instrument

Tests were conducted to determine the accuracy of the azimuth worm and worm wheel of an Akeley phototheodolite especially selected as being the best of a lot of 100 instruments. The results, as shown in Figure 1 of the EKC final report,[1] gave a maximum error of 0.2 mil for the worm wheel and 0.1 mil for the worm, or a total of 0.3 mil for the combination. Additional faulty features were found.

1. The method employed to eliminate backlash leads to excessive wear on the worm and worm wheel.
2. The measured backlash in the gear train that connects the azimuth and altitude angle counters to the worm shaft is approximately 0.1 mil.
3. The design of the leveling base is such that excessive tightening of the leveling screws may distort the azimuth worm wheel.
4. Two-man tracking was found to be impossible.

15.2.2 Askania Instrument

The Askania instrument employs a graduated circle for azimuth and elevation angle readings which, together with a fiducial reticle, makes possible readings to 0.5 min of arc. Tests of the azimuth circles of two instruments showed that the errors in the circle divisions were insignificant.

The eccentricity of one of the circles was only 0.00075 in., or 0.03 mil. The measured eccentricities of the main azimuth bearings, however, were 0.008 in. and 0.00035 in., corresponding to errors of 0.35 and 0.13 mil, respectively.

15.2.3 Conclusions

The Akeley phototheodolite could not be modified to conform to the desired specifications. The Askania phototheodolite could be made to yield the desired accuracy by the installation of new precision ball bearings for the vertical and horizontal axes. Consideration of other necessary changes, however, made it likely that the demands of the Services could best be met by the development of an entirely new instrument.

15.3 DESIGN PROBLEMS

The following theoretical considerations entered into the design of various components of the phototheodolites.

15.3.1 Camera

Lens

The decisive factor in determining the required lens diameter was photographic speed, not resolving power, since the minimum diameter required to resolve an angle of 0.1 mil at wavelength 5,600 A is only 0.26 in. At Fort Monroe good photographs were obtained during daylight hours with exposures of $\frac{1}{30}$ sec and focal ratios between $f/22$ and $f/45$. The Eastman Research Laboratory conducted tests which showed that satisfactory photographs of flash from shellbursts at night were obtained in $\frac{1}{30}$ sec at $f/5$ to $f/8$.

The maximum focal length of the camera lens was determined by the expected accuracy of linear measurement on the film. Experience showed that measurements could be made consistently with an accuracy of 0.001 in., corresponding to 0.1 mil at a focal length of 10 in.

Lens Mounting

In ordinary usage, slight lateral shifts of lenses in their mounts are permissible. In the phototheodolite, the lens must maintain a line of sight defined by its nodal point and the fiducial point in the film plane. This line must at all times be maintained perpendicular to the elevation axis. It follows also that the lens mount must be so designed that temperature changes or vibrations will not cause lateral shifts of the lens. The material chosen for the mount must be such that good focus is maintained over a range of temperature.

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When a worm and worm wheel are used for the determination of angles, the lenses must be counterbalanced to avoid undue loading of the worm wheel and to minimize the torque necessary for tracking.

Film Size and Shrinkage

The longest focal length desired for the phototheodolite is 48 in., which with 35-mm film gives a field of 15.6 mils. Since tests at Fort Monroe showed that, with fair tracking, the maximum error is 1.7 mils, the use of 35-mm film provides ample space for the dial readings and time counter.

Under the worst conditions, the film will change its dimensions by about 0.5 per cent between the time it is exposed and finally processed. However, since the target is never expected to be more than about 2 mils from the fiducial point, the maximum error introduced by film shrinkage is only about 0.01 mil.

Camera Drive

To simplify the problem of synchronization of target exposure with two phototheodolites, and also to simplify the mechanism for producing variable picture rates, an intermittent or "single-frame" mechanism was chosen in preference to a continuously driven cine-type camera.

Frequency of Picture Taking

In tracking target airplanes, the number of photographs per second required to define the flight path is determined by the maximum curvature of the path. On the reasonable assumption that $10g$ is the maximum acceleration that a plane can stand, it can easily be shown that with 3 or 4 frames per second the plane position can be located to within 1 yd. In shellburst photography, however, a rate of about 18 per second is required to record the burst on at least two frames.

Exposure Time

The maximum exposure time is determined by the expected accuracy of tracking, the requirement being that the rate of change of tracking error, when multiplied by the exposure time, shall be less than 0.1 mil. If a periodic tracking error is assumed, of amplitude 1 mil and period 3 sec, the required exposure time must be less than 0.05 sec. The same limitation applies to the time difference between the centers of the dial and target exposures.

15.3.2 Angle-Recording Dials

Exposure Time

The time of exposure on the angle-recording dials is determined by the maximum rate of tracking, the requirement being that the blurring shall be less than 0.1 mil. Assuming, for example, a target distance of 1,000 yd and speed of 150 yd per second, the angle to the target changes by 0.1 mil in less than 10^{-3} sec. The only satisfactory exposure device is an Edgerton lamp, with an exposure time of 10^{-4} sec. When two phototheodolites are employed simultaneously on the same target the exposure on the respective dials should also be synchronized to within 10^{-3} sec to avoid complications in the reduction of the data.

15.3.3 Leveling and Misleveling

The main requirements for the phototheodolite levels are high accuracy (error less than 0.1 mil), high sensitivity, and a means for restraining motion of the instrument in the leveling plane during the leveling operation.

Because of the earth's curvature, provision must be made for misleveling one of the two phototheodolites, in order that the angles at the instruments be measured in two parallel planes. Misleveling may be accomplished by putting on one leveling screw a dial graduated in divisions representing the distance between the two phototheodolites.

15.3.4 Bearing Accuracy

The bearing design must be such that the error contributed by eccentricity is constant and only a small fraction of the overall error of the instrument. If the graduated circle or the worm wheel is 16 in. in diameter, a linear value of 0.001 in. for the eccentricity corresponds to an angular error of 0.025 mil.

15.3.5 Atmospheric Refraction

Available information on daytime astronomical "seeing" is not sufficiently accurate to determine whether atmospheric conditions would interfere with the performance of a 0.1-mil phototheodolite. Tables of refractive errors and a useful bibliography have been compiled.[2]

15.4 CONSTRUCTION OF THE EASTMAN RECORDING PHOTOTHEODOLITE

Figures 1 and 2 show respectively a photograph of the completed phototheodolite and a layout of the instrument. The mounting of the camera is of conventional design. A yoke free to rotate about the vertical axis supports the horizontal axis, about which the optics and camera swing in elevation. The adopted design permits maximum flexibility and sky coverage.

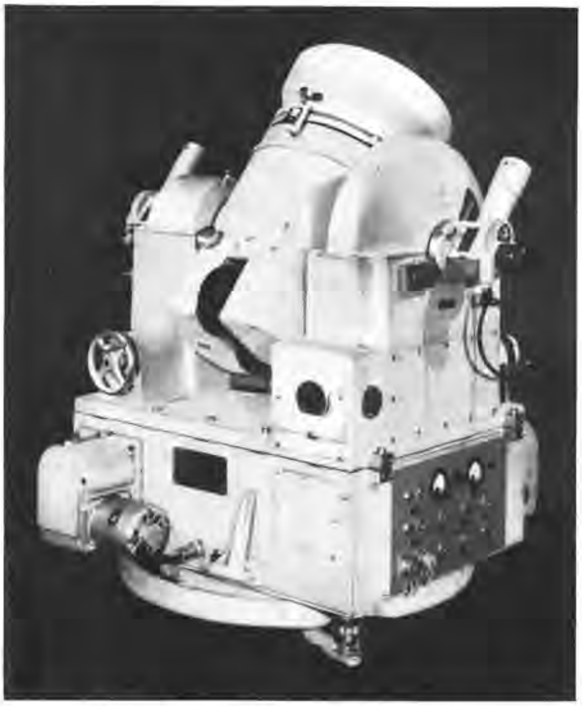

FIGURE 1. Eastman phototheodolite.

15.4.1 Angle Measurement

Worm and worm-wheel systems were chosen in preference to a graduated circle partly because it is difficult to make a graduated circle with the smallest division equal to 0.1 mil (equals 0.000785 in.) for direct reading without a vernier on a 16-in. diameter. The circle would need to be imaged on a fiducial reticle, and readings would be difficult to make as compared with a simple counter. Moreover, perfect tracking requires the use of extremely accurate worms and worm wheels, which also can easily be equipped with counters.

DESIGN AND CONSTRUCTION OF WORM AND WORM WHEEL

The worm and worm wheel were constructed according to methods developed and employed by the Gould and Eberhardt Company, of Irvington, New Jersey. The worm is of the *dual-lead* type, in which one side of the tooth profile is generated with a standard lead, and the other side with a lead slightly greater or smaller than the standard. The resultant worm will then have a thread whose profile increases in size from one end of the worm to the other. A wheel to fit this worm is made by using a hob made exactly like the worm. The corresponding section of the worm that was used in the hob will then mesh with the worm wheel with zero backlash. If more backlash is desired, the worm is moved in an axial direction, thus bringing into mesh a thinner section of the thread. This method of design eliminates backlash without disturbing the theoretical center-to-center distance between worm and worm wheel.

The diameter of the worm wheel is 16 in., this being the minimum diameter that seemed likely to allow 0.1 mil accuracy with the expected eccentricity, backlash, and tooth and thread errors. The worm wheel was designed to have 128 teeth, and, since one revolution of the worm wheel corresponds to 360 degrees or 6,400 mils, each turn of the worm corresponds to 50 mils, a convenient number for a counter. The diameter of the worm thread is large (4.465 in.) which results in a very small helix angle, so that flexure of the worm shaft has a negligible effect on the measured angle.

The construction of the worm and worm wheel is the same for azimuth and elevation, except for the hub design. The worm is made of SAE 4620 steel, seasoned and hardened to

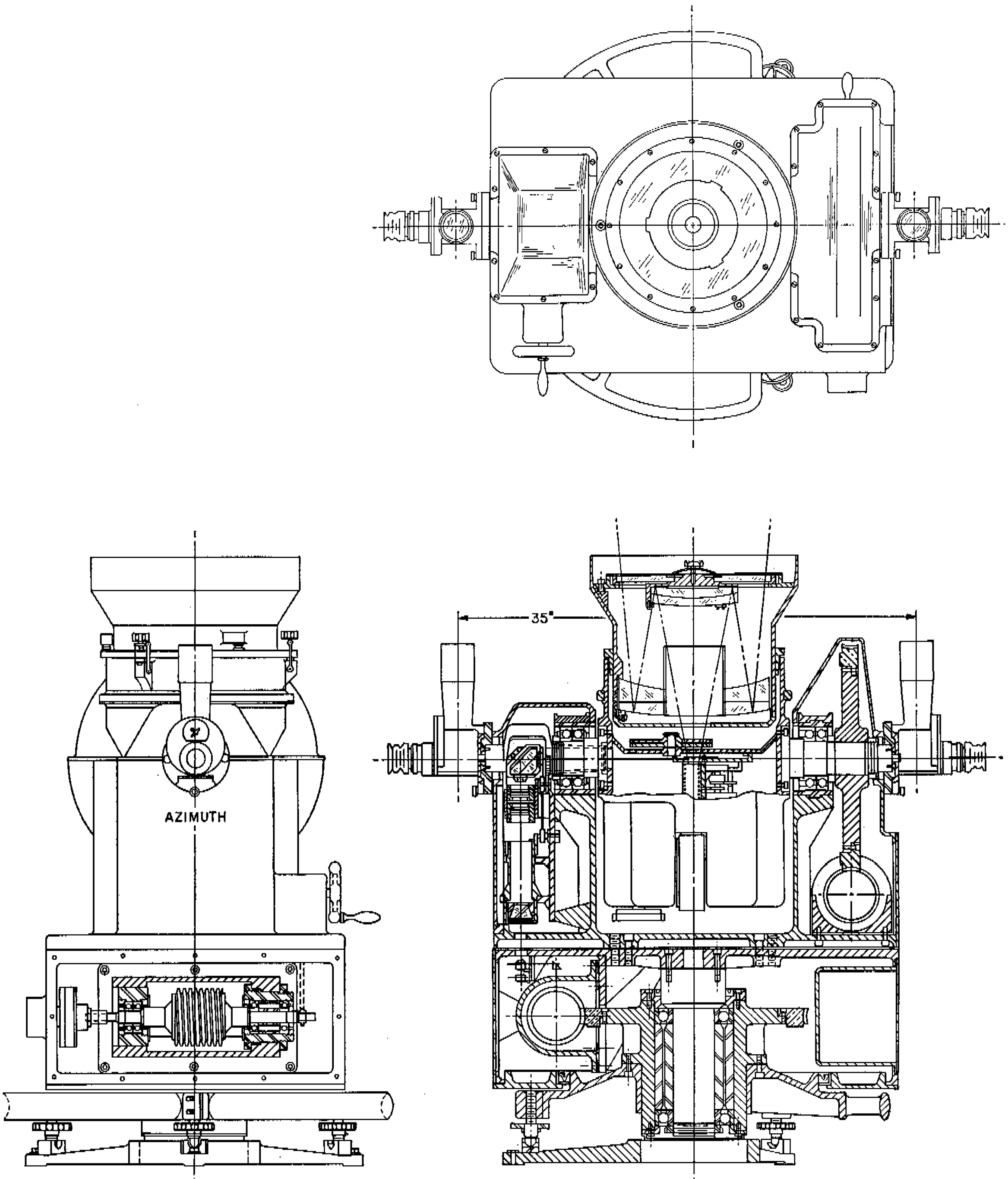

FIGURE 2. Layout of phototheodolite.

a Rockwell hardness of C58-63. The wheel is made with a No. 15 chilled cast-bronze periphery, Brinell hardness 74-93. The periphery casting, which was made by the Lumen Bearing Company, Buffalo, New York, was fitted to a Type B Meehanite cast hub made by the American Laundry Machinery Manufacturing Company, Rochester, New York.

In the construction of the worm wheels, a proof diameter and a face were turned on the wheels while they were rotated in their working bearings. These surfaces were then used to

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orient the wheels on the master hobbing machine workbench so that they were concentric with the table's axis of rotation. When the teeth were cut, they were thus generated about the working axis of the wheel. The worm was also provided with a proof diameter, which was ground with the same setting used for grinding the thread, and used to determine the amount of eccentricity in the worm bearings.

The fitting of the worm and wheel was accomplished by a trial and error process. The worm was ground initially so that the large end was larger than the drawing specified by about 0.0008 in. The worm and wheel were assembled, and the center-to-center distance adjusted, by means of shims, to the theoretical value, which is the distance used in hobbing the teeth on the wheel. The theoretical center-to-center distance was held throughout the fitting process. The teeth were then coated with a very thin layer of a mixture of red lead and oil, and, with the backlash adjustment at the loose end, the worm was brought into mesh with the wheel. The worm was then oriented until the red lead indicated the best bearing between the two parts. The worm was then reground to compensate for faulty tooth contact, and the testing process was repeated. On the average, about six trials were necessary before satisfactory results were obtained. The worm housing was then pinned in place and the worm removed for a final grinding to size.

Bearings

The bearings selected for the phototheodolites were manufactured by the New Departure Corporation. They are Radax Ultraperfex preloaded ball bearings, each set produced by selective assembly from thousands of parts, in which the bore, outside diameter, and eccentricity are held to 0.0001 in.

Various other types of bearings were investigated. For example, sleeve bearings combined with ball thrust bearings are of sufficient accuracy, but experience with existing phototheodolites showed that they do not maintain their precision. On the other hand, preloaded ball-bearing designs are used in precision shop equipment and hold their accuracy after years of continuous operation.

Vertical Axis. The center of the azimuth worm-wheel hub provides the housing for the bearings, which are separated in order to give vertical rigidity to the axis. The entire weight of the instrument is taken by the vertical bearings, through the hub, which is fastened to the main base, and thus to the leveling screws. The result of eccentricity tests for two vertical axis assemblies was 0.000025 in., and for the third, 0.00005 in.

Horizontal Axis. Figure 3 is a cross-sectional view of the horizontal axis. Two pairs of preloaded bearings are used, one set on each side of the camera. For convenience of assembly, the yoke housing is split and the bearings located in a thick cartridge that seats in the split housing. The worm-wheel side of the horizontal axis is anchored to the yoke casting by means of an angular key which maintains the worm wheel in a fixed position with respect to the worm. The other end of the axis is free to move should differential expansion take place. The recesses for the trunnions were machined with high precision and each trunnion was finish-ground separately, resulting in an assembly in which the two trunnion axes are concentric within 0.00015 in. The result of eccentricity tests for two assemblies was 0.00005 in. on one and 0.00010 in. on the other.

Worm Axis. Figure 4 is a cross-sectional view of the worm assembly. The construction is similar to that of the horizontal axis. One end of the worm is adjustable for the removal of backlash, but once adjusted it remains fixed with respect to the housing. Because the cartridge that houses the bearings at the adjustable end is necessarily long to provide enough movement, the ball bearings are separated with spacers to bring them close to the ends of the cartridge. Eccentricity tests indicated that the ball bearings are of the same precision as those employed in the vertical and horizontal axes.

15.4.2 Camera Mechanism

The camera mechanism is of the single-frame type, in which a clutch couples a continuously operating driver to the mechanism. The clutch is a mechanical, self-energizing type developed

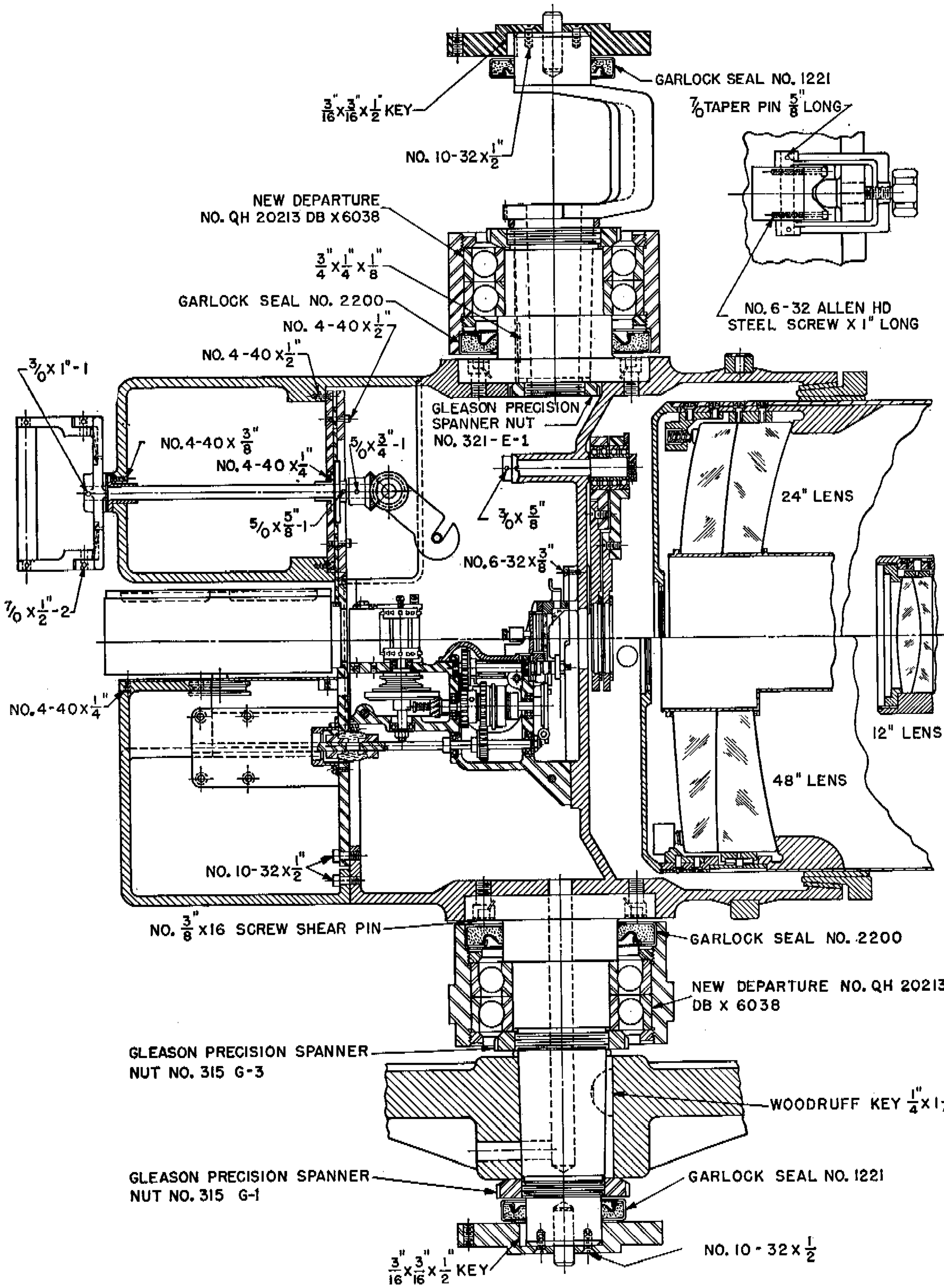


FIGURE 3. Horizontal axis assembly.

[redacted]

especially for the phototheodolite. Magnetic types were considered and found suitable, but the mechanical version offered better design flexibility.

A schematic view of the clutch is shown in Figure 5. A continuously running gear is driven by a 60-c, 110-v synchronous motor operating at 1,800 rpm through a 3/2 gear reduction, the time for one picture cycle being thus 0.05 sec. The sequence of operation is as follows: When the solenoid is energized, the engaging disk is freed, and is acted upon by the torsional spring through shaft A, resulting in a small counterclockwise angular displacement as viewed from the spring end. Cam action on the right-hand side of the engaging disk causes it to move axially and to be coupled to the driven gear. When the solenoid is de-energized, the armature stops the engaging disk, and the inertia of the system causes cam action on the left-hand

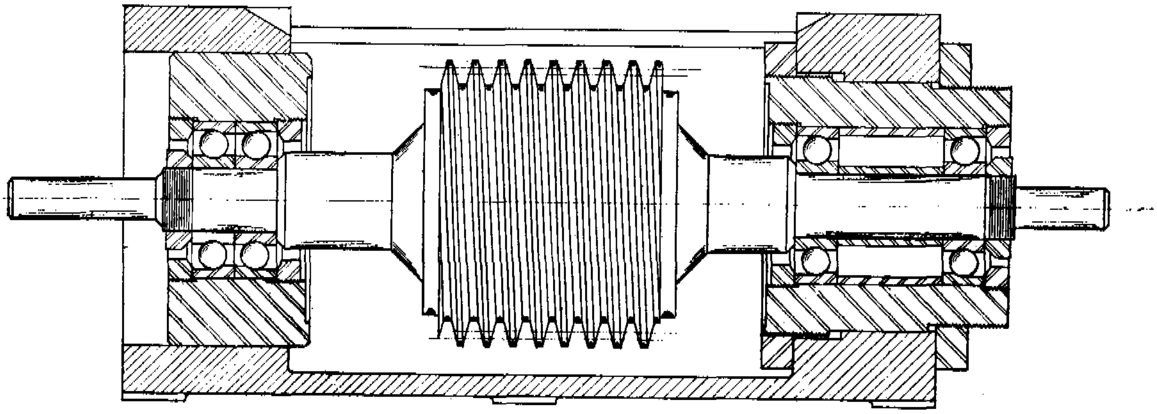


FIGURE 4. Worm assembly.

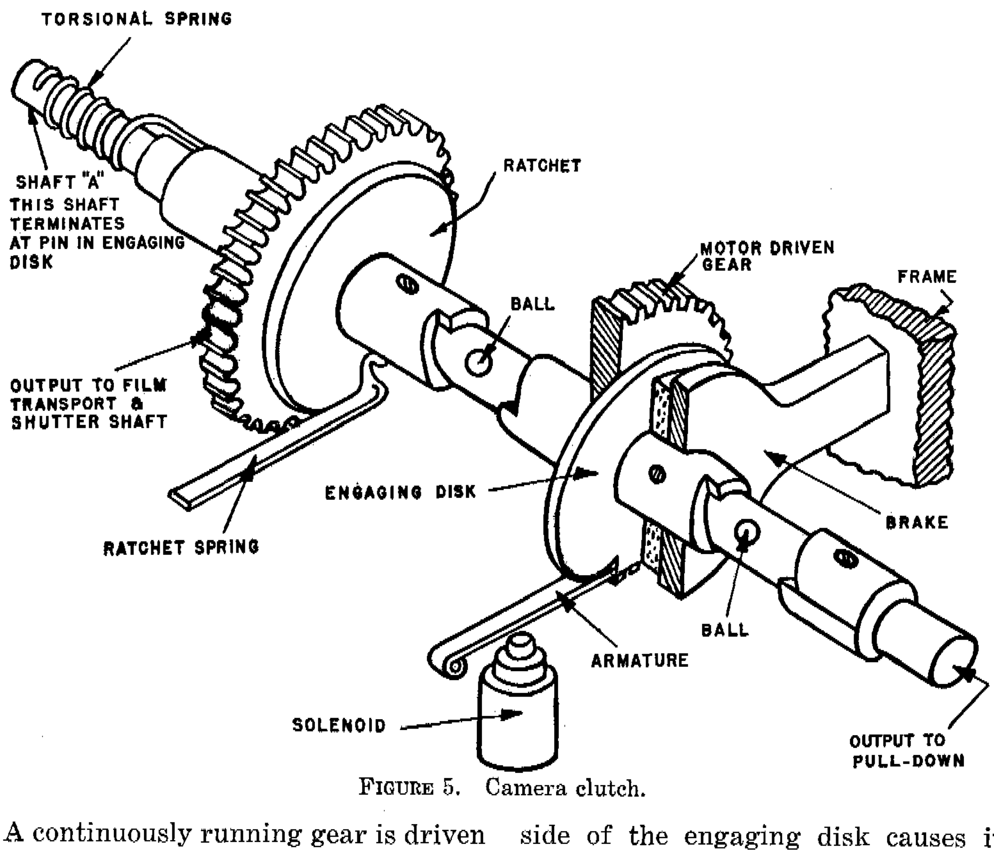


FIGURE 5. Camera clutch.

side of the engaging disk to displace it axially against the brake. The ratchet spring prevents the torsional spring from unwinding until the solenoid is re-energized.

It was not possible to operate the camera mechanism at frequencies much greater than 10 frames per second. When a higher speed is desired, the motor is coupled continuously to the mechanism, resulting in a speed of 20 frames per second.

An Eyemo movement is used for the pull-down and a single sprocket supplies and takes up the film. The shutter is a sector, mounted on its own shaft, and geared one-to-one to the clutch shaft. Since the sector opening is 72 degrees and the complete picture cycle 0.050 sec, the time for one exposure is 0.010 sec. The film chamber is a standard type made by the Akeley Camera Company, its capacity being 200 ft of 35-mm film. A footage indicator is built directly into each film chamber. The fiducial mark consists of a cross, open in the center, engraved on a glass plate.

15.4.3 Optics

Lenses

The design of the lenses was largely dependent on the aperture ratio necessary for night photography. The night photography requirement was taken as $f/5$ at $\frac{1}{30}$ sec, or $f/2.8$ at the adopted exposure of 0.010 sec. Since a 48-in. lens at $f/2.8$ requires a lens diameter of 17 in., NDRC agreed to a modification of the original specifications to include a 48-in. lens at $f/5.6$, a 24-in. lens at $f/2.8$, and a 12-in. lens at $f/4$.

The choice of optical system for the 24-in. and 48-in. lenses was governed mainly by considerations of size and weight. The use of a normal-type telephoto lens was ruled out for the following reasons:

1. The overall length, that is, the distance from the front vertex to the focal plane, is about 80 to 85 per cent of the focal length, or about 40 in. for a 48-in. lens.

2. To correct adequately the spherical aberration in a 48-in. lens more than 8 in. in diameter, requires an excessive number of lens components of prohibitive weight and leverage.

3. An aperture of $f/2.8$ for the 24-in. lens would be difficult to achieve with a telephoto lens.

4. A normal telephoto lens suffers considerably from secondary spectrum residuals and from sphero-chromatism (chromatic variation of spherical aberration).

5. The temperature coefficient of back focus is large in a telephoto lens.

Many of the foregoing disadvantages are not present in a mirror system. Chromatic aberrations are absent and the overall length can be made much shorter than with a normal telephoto lens. The temperature effect is very small and is almost perfectly compensated by the use of a steel lens barrel.

Three types of mirror systems were considered:

1. A classical Cassegrain system with conic-section mirrors and a Ross corrector lens was not adopted mainly because the Eastman group had no experience in the generation of conic-sections, and the time factor was important.

2. A conventional Schmidt mirror system was not undertaken because its overall length is twice the focal length.

3. A mirror-lens combination, in which a pair of weak achromatic lenses, silvered on the back surfaces, is mounted as a Cassegrain system, was the arrangement actually adopted (see Figures 6, 7, and 8 for the lens specifications and diagrams). The function of the lenses is to remove the spherical aberration of the mirror surfaces. Careful balancing of the refractive errors between the front and rear lens systems made possible the elimination of both spherical aberration and coma. Curvature of the 1-in. diameter field was negligible.

The gain in length resulting from the use of this type of system is shown in the following table:

Lens	Effective Aperture	Total Length	Total Length Divided by Focal Length
24-in.	$f/2.8$	13.7 in.	57 per cent
48-in.	$f/5$	20.1 in.	41 per cent

The only noticeable aberration residual is secondary spectrum, of the following amount, as computed relative to the sodium D line:

[redacted]

Line	24-Inch	48-Inch
C	−0.43 mm	0.55 mm
D	0.00 mm	0.00 mm
F	+0.13 mm	+0.44 mm
G′	−0.08 mm	+0.05 mm

The optics for three 24-in. lenses were made by Perkin-Elmer Corporation and mounted by the Eastman group in cells made in Rochester.

FORMULA: 4-P-362 SPEED: f/4.0

12-INCH LENS FOR PHOTOTHEODOLITE

EQUIV FOCUS: 305.00MM (12") BF = 234.95 FF = 228.67

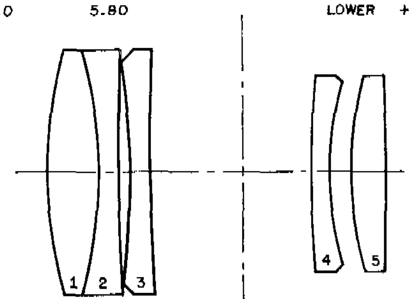
ANGULAR FIELD: 2.386° (1-INCH DIAMETER)

LENS	GLASS	n_D	$n_{G'}$	ν
1	DBC − 3	1.61088	1.62450	57.2
2	LF − 4	1.57511	1.59264	42.8
3	CROWN FLINT	1.52543	1.53771	54.8
4	DF − 2	1.61700	1.63929	36.6
5	EK − 11	1.69677	1.71255	56.1

ALL TEST GLASS RADII

DIAPHRAGM	OPENINGS
f/4.0	65.30
5.6	46.64
8.0	32.65
11.0	23.75
16.0	16.32
22.0	11.87
32.0	8.16
45.0	5.80

RIM RAYS	2.386°
UPPER	−0.015
0.7 UPPER	−0.015
PRIN	000
0.7 LOWER	+0.012
LOWER	+0.024



SURFACE	CL APER	TRIM
1	76.20	78.20
3	72.34	
4	72.34	78.20
5	71.44	
6	60.66	62.66
7	59.44	
8	60.10	62.66
9	59.32	

SURFACES 3 AND 4 MEET AT A DIAMETER OF 72.34 MM

SPHERICAL ABERRATION	COMA
f/4.0 (D) −0.165	+0.016
f/5.6 (D) −0.113	−0.015

AXIAL COLOR: G′−D −0.012; C−D +0.253

LATERAL COLOR (2.386°)
(G′−D) 00
(C−D) +0.003

PETZVAL SUM(100) = +0.005765
RATIO = +1.73

FIELD	ΔY	ΔF″	ΔF′
2.386°	−0.003	−0.125	−0.079

FIGURE 6. 12-in lens design.

The components for three 48-in. lenses were made entirely at the Hawk-Eye Works of Eastman Kodak Company. Great pains were taken in rotating the four elements of each lens combination relative to each other, in order to secure the best possible compensation of surface irregularities, and in laterally aligning the front and rear members to eliminate axial coma.

Three 12-in. $f/4$ lenses of the projection (Petzval) type were also made at the Hawk-Eye Works. These gave excellent images when tested on an ordinary lens bench.

In the event that the 48-in. mirror-type lens should not prove satisfactory, NDRC requested the design of a 48-in. $f/11$ normal telephoto-type lens. For this purpose, a 15-in. $f/11$ telephoto lens, already on hand, was modified to increase its focal length to 48 in. Specifications for this lens are given in Figure 18 of the EKC final report.[1a]

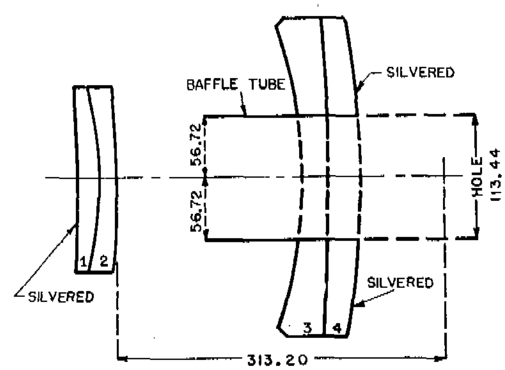
FORMULA: 28-R-210 SPEED: f/2.8

CASSEGRAIN SYSTEM FOR PHOTOTHEODOLITE

EQUIV FOCUS: 609.6MM (24") BACK FOCUS: 313.2

ANGULAR FIELD: 1.69°

LENS	GLASS	n_D	$n_{G'}$	ν
1	DBC − 3	1.61088	1.62450	57.2
2	LF − 3	1.57500	1.59317	41.4
3	BSC − 2	1.51700	1.52709	64.5
4	DF − 2	1.61700	1.63929	36.6



SURFACE	CL APER	TRIM
1	154.40	168.00
3	168.00	
4	275.28	291.00
6	289.00	

SPHERICAL ABERRATION		COMA
f/2.8 (D)	0	+0.154
f/4.52 (D)	−0.015	+0.110

PETZVAL SUM (100) = −0.015617
RATIO = −0.64

FIELD	ΔY	ΔF″	ΔF′
1.2°	+0.035	−0.080	−0.209
1.69°	+0.060	0.000	−0.393

FIGURE 7. 24-in. lens design.

TESTS OF LENS RESOLUTION

Photographic tests of the resolution of each phototheodolite lens were made by EKC, using a lens-to-target distance equal to fifty times the focal length of each lens. The target material was ½-in. thick composition board 35.35 in. square, or fifty times the size of the target area on the phototheodolite film. Cemented to the board was a series of small resolution charts

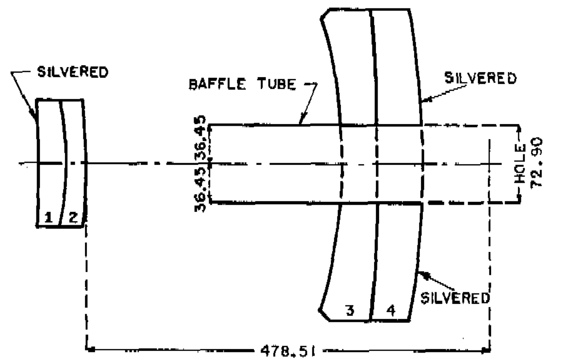
FORMULA: 5-R-212 SPEED: f/5.0

CASSEGRAIN SYSTEM FOR PHOTOTHEODOLITE

EQUIV FOCUS: 1219.20 (48") BACK FOCUS: 478.51

ANGULAR FIELD: 0.597° (1 INCH DIAMETER)

LENS	GLASS	n_D	$n_{G'}$	ν
1	DBC-3	1.61088	1.62450	57.2
2	LF-3	1.57500	1.59317	41.4
3	BSC-2	1.51700	1.52709	64.5
4	DF-2	1.61700	1.63929	36.6



SURFACE	CL APER	TRIM
1	111.70	124.00
3	122.00	
4	275.28	291.00
6	284.00	

SPHERICAL ABERRATION		COMA
f/5.0	+0.013	+0.026
f/11.3	−0.033	−0.013

PETZVAL SUM (100) = +0.004441

RATIO = +2.25

FIELD	ΔY	ΔF"	ΔF'
0.597°	+0.013	−0.113	−0.386

FIGURE 8. 48-in. lens design.

which formed a cross extending to the corners. Each chart consisted of eight line patterns of six horizontal and six vertical lines, the spacing varying in $\sqrt{2}$ steps from 10 lines per mm to 112 lines per mm, as measured at the film plane. The center chart was placed with the lines vertical and horizontal and those in the cross with the lines radial and tangential. To facilitate focusing, a 35-mm film carrier was mounted on a jeweler's lathe compound. For illumination of the target, an Edgerton flash lamp was employed in order to obtain exposures short enough to minimize the effect of building vibration.

Three types of film were used. Super-XX film was developed in D-19 for 8 min at 68 F, and Shellburst Pan and Microfile in D-11 for 5 min. The use of Super-XX and the means of development were recommended by NDRC to provide a basis for comparison between the phototheodolite lenses and high-grade aerial camera lenses. Shellburst Pan was used because the phototheodolites will normally operate with this type of film. The use of Microfile film, with a minus-red filter over the light source, gives the maximum possible resolution.

The results are summarized in the following table:

Lens		Super-XX	Shell-burst Pan	Microfile
		(lines per mm)		
12-in. f/4	No. 1	20	20	56
	No. 2	28	28	80
24-in. f/2.8	No. 1	14	14	40
	No. 2	14	14	56
	No. 3	14	14	28
48-in. f/5	No. 1	14	20	40
	No. 2	14	14	40
	No. 3	14	14	28
48-in. f/11	No. 1	14	20	56
	No. 2	20	20	40

The resolution of all the lenses is considerably less than that of high-quality aerial camera lenses developed by NDRC. The resolution of the latter on Super-XX has been recorded at 30 lines per mm at $f/11$, and at 60 lines per mm at $f/2.8$.

The testing procedures departed in two respects from those commonly employed in testing aerial cameras. First, the phototheodolite tests were conducted with 6-line rather than with the customary 3-line targets. The resolving power of the phototheodolites is accordingly favored, although probably by no more than about 10 per cent. Second, the target spacing varied by $\sqrt{2}$ steps. Usually $\sqrt[3]{2}$ or $\sqrt[6]{2}$ steps are employed, which provides a more accurate determination of resolving power.

LENS MOUNTS

The mount for the 24-in. lens is shown in Figure 9. Since all the mounts were designed to produce the same moment about the horizontal axis, only one counterweight is necessary. Each lens is located in its mount following the principles of kinematic design. The lens components are supported axially against three stationary pads spaced 120 degrees apart, with pressure applied by spring-loaded pads directly in line with the stationary pads. Radial location is accomplished by three additional pads, two stationary and one spring loaded, and spaced 120 degrees apart. The spring loading is in line with and at the fixed end of the horizontal axis, which should act to maintain the

line of sight perpendicular to the horizontal axis and intersecting the fiducial reticle of the camera despite changes in temperature. In the 24- and 48-in. assemblies, the secondary lens is supported by a thick glass plate which also provides a cover glass for the whole lens system.

FIGURE 9. 24-in. $f/2.8$ lens mount.

In the Cassegrain systems, daylight from the sky is prevented from reaching the film directly by a metal baffle tube, which is attached to the hole in the large mirror and projects inwards to the point at which the useful rays going and coming intersect each other. In the 48-in. system, a small additional exterior "sunshade," projecting beyond the front window, is necessary.

To permit focusing and alignment of the lenses with respect to the camera focal plane, an auxiliary ring was interposed between the camera and lens. On one side of the auxiliary ring is fastened the lens assembly, and on the other are three ball studs that mate with three hardened V blocks with U-shaped clamps integral to the camera housing. The ball studs are so spaced that the auxiliary ring will fit to the camera in only one position. Good focus and alignment of the lens unit are obtained with shims placed at the auxiliary ring.

To obtain lightweight and strong sections, the lens barrels were made of welded steel plate. Corrugations rolled into the barrel of the 48-in. lens give added stiffness. The optics for each of the 24- and 48-in. lenses weighed about 40 lb and the entire lens assemblies approximately 75 lb each. Most of the weight of the 12-in. lens assembly is in a large casting that goes between the lens barrel and the auxiliary ring.

For the 48-in. $f/11$ telephoto lens, the design of the mount was greatly complicated by the need for thermal compensation. Because of the probability of temperature gradients in the mount, it was doubtful that successful temperature compensation could be obtained from a mount of practical design. A compromise was reached involving a mount made of material with a coefficient of thermal expansion approximately matching that of glass. For a temperature change of 100 F, and in the absence of temperature gradients, the calculated change in focus is of the same order of magnitude as the difference in focus between distances of 2 miles and infinity.

15.4.4 Exposure Control

A conventional iris diaphragm for exposure control could not be used because the outside diameter of the lens mount would have to be increased considerably, and the theoretical location of the diaphragm in a mirror-lens system is between the reflecting surface and the refractor elements.

The adopted plan employs neutral-density filters close to the image plane. Space limitations forbade the use of a single disk with sufficient filters to accommodate the entire range of exposure conditions. Instead, two sectors, containing three filters each, are used in combination to effect nine different exposures. The filters are made of glass, with essentially no lens power and with parallel faces. Each sector contains one section of clear glass and two filters, the four filters having transmission factors of 50, 25, $12\frac{1}{2}$, and $1\frac{1}{2}$ per cent. The filter transmissions were designed for use with Shellburst Panchromatic film. Because the filters were of different thicknesses, a piece of clear glass was cemented to each, and all were then

ground and polished to the same thickness. Low-reflection coatings were applied to both faces of each filter.

The filter sectors are actuated by two levers that extend to the outside of the camera housing. A table of the lever settings appropriate to each exposure is attached to the phototheodolite.

The 12-in. lens is also supplied with an iris diaphragm to provide, if necessary, a secondary means for controlling the exposure.

15.4.5 Camera Viewer

To facilitate the alignment of the phototheodolite and to make possible accurate boresighting, a camera viewer is supplied with each instrument. The viewer consists essentially of an objective lens, a reticle, and an eyepiece, and magnifies the camera lens image three times. When the viewer is properly oriented, the reticle is aligned with the camera fiducial marks. Focusing of the viewer is accomplished when the parallax between the two reticles is reduced to zero. The viewer is easily attached to the film side of the camera with two thumbscrews, but before it can be used the pressure pad in the film gate must be removed.

15.4.6 Angle Recording

INDICATING DRUMS

A cutaway view of the azimuth angle indicator is shown in Figure 10. A planetary gear system is employed, in preference to a Veeder Root type counter connected directly to the worm. The latter system suffers from the disadvantage that the readings must be altered when the instrument is turned through more than one revolution. The readings are made from two drums, one graduated in steps of 0.1 mil, which is connected directly to the worm, and the other graduated in 100-mil steps and connected to the output of the planetary gear. Since one revolution of the worm equals 50 mils, the planetary system is designed so that the output gear rotates through $\frac{1}{128}$ of a revolution per revolution of the worm (6,400 mils = 360 degrees). By means of controls external to the instrument, the azimuth 0.1-mil drum may be released from the worm shaft and rotated to any desired orientation setting. The

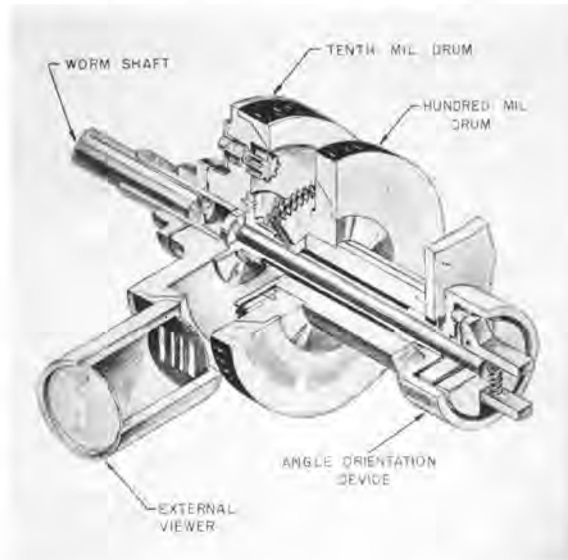


FIGURE 10. Azimuth angle indicator.

dials are illuminated by a flashing Edgerton lamp. Translucent dials are used in preference to reflecting dials because of their higher optical efficiency and the relatively high degree of heat dissipation associated with the use of Edgerton lamps. The drums are made of Lucite, with the figures engraved on a coat of black paint on the periphery. Light from the flashing lamp is reflected directly by a 45-degree conical surface underneath the periphery of the drums, thus producing translucent figures on a black background. Black figures on a white background are less desirable because of a smaller permissible variation in exposure for readable images.

The 0.1-mil drum is divided into 500 divisions, every tenth division being numbered from 0 to 49. Adjacent to these figures is a second row of numbers from 0 to 49, but with the zero displaced angularly by 90 degrees from the zero of the former row. Similarly the 100-mil drum is numbered from 0 to 63, and a second row of numbers is displaced by 90 degrees. For photographic purposes an aperture plate with a fiducial mark covers up the outer rows

[redacted]

of figures, exposing the graduations and the inner rows of figures. For visual reading of the dials, a second aperture plate covers the inner rows of figures and makes visible the outer rows and graduations. A magnifying lens and incandescent lamp are provided at the external reading point.

EDGERTON LAMPS

Three No. 14 General Electric flash lamps in series are used to illuminate the azimuth and elevation drums and the time counter (see following section). Preliminary tests showed that the Edgerton lamps became exceedingly hot when flashed at a frequency of 20 per sec, and that about 10 per sec represented a safe limit. Accordingly, when photographs are taken at the rate of 20 per sec, the data appear on every other frame and must be interpolated for the intervening frames.

TIME COUNTER

Simultaneous photography by two phototheodolites requires the use of a time counter. For this purpose a Bell Telephone type counter developed especially for the AAA board was employed. Its characteristics are low-inertia, decimal-type reading, and actuation at a frequency of 20 counts per sec by a 50-v pulse.

A second so-called "course counter," which is manually operated external to the instrument, is used to designate the number of the course or test under investigation. The counters are covered by an aperture plate on which is printed the serial number of the phototheodolite. The counters may be read directly through a small window external to the instrument.

To increase the optical efficiency of the time and course counters, a very thin 10-sided aluminum ring, with raised numbers chrome-plated and buffed, was pinned to each plastic drum.

FILM READING

A representation of a strip of film, as it would be taken with the phototheodolite, and a 3× magnified view of one frame are shown in Figure 11. The numbers and graduations to the left in the angle data spaces are from the 100-mil drums, whereas those to the right, which form a vernier scale, are from the 0.1-mil drums. The fiducial mark is in the center of the frame, between the two scales. The azi-

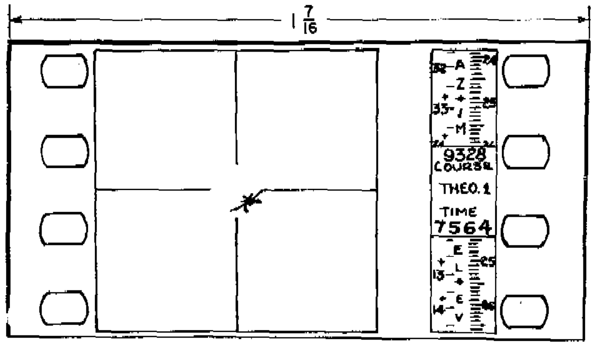


FIGURE 11. Single frame 35-mm film as proposed for phototheodolite viewed through back of film.

muth reading is 3,274.9 mils and the elevation reading 1,325.5 mils.

OPTICS

A rather elaborate optical system is required in order to bring all of the data to the small area provided on the film. The layout, which is shown in Figure 12, is divided into four parts. There is a separate optical system for the azimuth, elevation, and the time and course readings, each with its own objective lens. The rectangle of data is formed in a field lens by the prisms and lenses of each of the three optical systems, after which an additional lens and prism assembly images the data on the film plane. Prisms were used exclusively instead of front-surface mirrors, because the latter lose their reflectivity in a relatively short time. In passing through the final optical assembly, the light beam traverses an antirotation prism, which rotates at half the speed of rotation of the horizontal axis and prevents the data image from rotating with respect to the film as the camera is moved about the horizontal axis.

15.4.7 Aided Tracking and Telescopes

The design of the aided-tracking unit before the completion of the instrument presented a formidable problem, since only a rough estimate could be made of the exact power requirements. The design adopted was evolved by

[redacted]

Eastman Kodak Company, from study of the aided-tracking unit in a captured German Director. A sector of a ball is mounted so that it can be driven at a constant speed about a diametral axis and is capable also of being rotated

The load that a ball can withstand varies as the second power of the diameter. Therefore, with sufficiently large diameter balls, the desired torque output can be obtained without the use of an amplifier. The difficulty with the Ger-

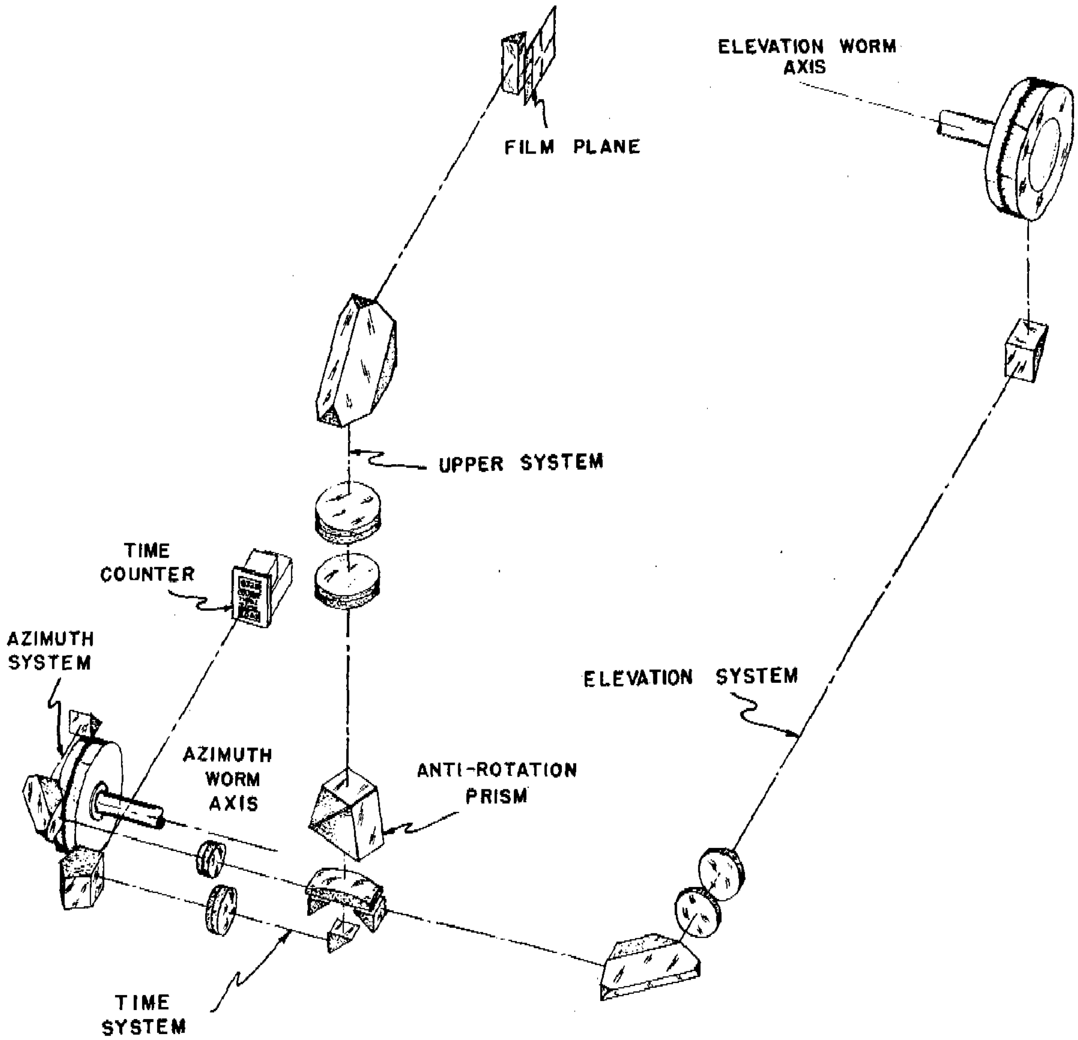


FIGURE 12. Data recording optics.

about a second diametral axis at right angles to the first. A slice out of the midplane of another ball is mounted with its periphery tangent to the ball sector. With the constant-speed axis of the sector perpendicular to and intersecting the axis of the ball disk, no motion is imparted to the disk. But, as the sector is rotated about the other axis, the disk is driven in one direction or the other. Thus, the rate of tracking in either azimuth or elevation is made proportional to the displacement of a handwheel.

man system is that, at low or zero rates of tracking, the ball disk tends to wear a hole in the sector. To remedy this difficulty, two ball disks were placed equidistant from the center of the sector and connected by a differential gear (see Figure 13). Steel equivalent to that used in ball bearings is used for the sector and disks, and the moving parts operate in a bath of oil.

For tracking, the phototheodolite is equipped with standard M-17 telescopes of 8 power and

8 degree field. They are used with Army fire-control equipment and have proven usable with good aided-tracking units, where the accuracy obtained was within 0.3 mil. Consideration was given to the use of higher magnification or of binocular telescopes to improve tracking accuracy, but the latter in particular offered too serious a complication to the design.

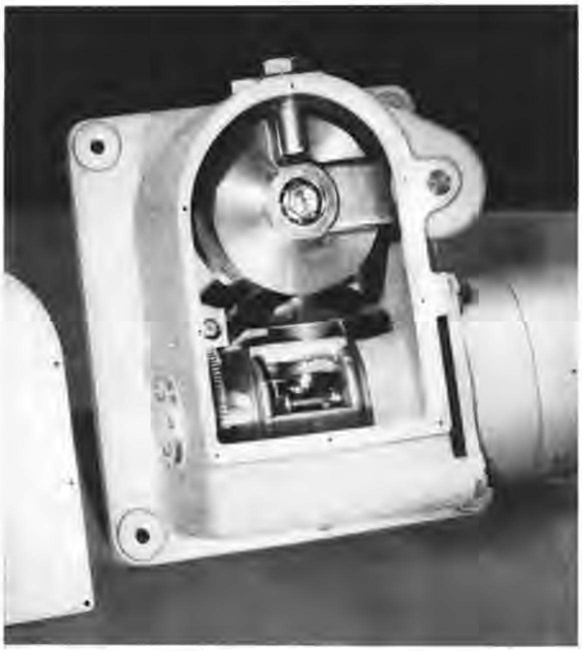


FIGURE 13. Aided tracking unit.

15.4.8 Levels

The level vials were obtained from the firm of W. A. Moyer and Son, of Parkers Landing, Pennsylvania, which also supplies levels of high precision to the U. S. Coast and Geodetic Survey Division. The levels made by this firm are of the cylindrical type, ground on the inside surface, with accuracies as high as 1.9 sec per millimeter displacement of the bubble.

The higher the angular value of each division, the greater is the time required to bring the bubble to equilibrium. As a compromise between extreme accuracy and slowness of operation, a value of 10 sec per millimeter was adopted, which should make possible satisfactory leveling to 4 or 5 sec of arc.

A special mount was designed and constructed which decreases the danger of breakage during adjustment. In the standard-type mount, the tube containing the vial usually has solid ends with two "ears," one extending from each end. In the Eastman design, a washer with one flat and one spherical side is inserted between the faces of the ears and adjusting nuts. The nuts that bear on the washers are made with a concave conical face. The washer thus seeks a new position with respect to the nut when the latter is adjusted.

Leveling of the phototheodolite is accomplished by three fine-thread screws, having large hand grips and spherical ends that rest in V blocks on the base. The advantage of this system is that if the instrument is removed and replaced, the center of the vertical axis will always come to rest in the same point on the base, regardless of temperature change.

The three leveling legs are placed 120 degrees apart on a $12\frac{1}{2}$-in. radius, and the thread was so chosen that one revolution of the screw produces a 2-mil change in angle. Split bearings, with clamping screws, are used for the leveling screws.

To provide for "misleveling" the Number 2 instrument, a dial is attached to the face of one leveling hand grip, with graduations every 1,000 yd of base line from 0 to 12,000. The dial is guided radially but is held by friction to the hand-grip surface. In operation, the instrument is placed with this leveling leg approximately on the base line facing the other station, and leveled, after which the dial is set on zero and the screw turned the proper amount for misleveling.

15.4.9 Alignment of the Axes

To insure perpendicularity of the tracking axes, provision has been made for adjusting the horizontal axis with respect to the vertical, a unique feature of the Eastman design. Consideration was given to applying the necessary adjustment to the bearings on one side of the horizontal axis. Self-aligning ball bearings of the required accuracy could not be obtained, however, and an additional drawback was the

certainty of disturbing the mesh between the elevation worm and worm wheel with this type of adjustment.

The solution adopted was to divide the instrument into two main sections, the upper carrying the horizontal axis and the lower the vertical axis. Recesses were milled around the periphery on the top of the lower section. The bottom of the upper section, which was machined and used as a datum plane for boring the horizontal bearings, was set on shims placed in the recesses of the lower section. Clamping screws are placed adjacent to each shim. When the condition of the two axes has been determined, the shims are varied in thickness to effect proper alignment. Either wedge-shaped or uniform-thickness shims may be used, depending upon the amount of correction desired.

15.4.10 Seals

Extreme precautions were taken to exclude all foreign matter that might interfere with the operation of the instrument. A Garlock seal consisting of a type L neoprene insert is used for every turning member that extends to the outside of the instrument. Type L inserts are softer than the standard types used in high-pressure oil systems and are used especially to keep out small particles of foreign solids. All covers fit into recessed machine surfaces in order to exclude particles that might hinder operation of the worm wheel. Flange tubes mating with Garlock seals are employed for connecting parts between the upper and lower sections. The electric power pack is in a recessed cavity that separates it from the inside of the instrument. The control panel may be removed and repairs made to the power pack without contaminating the instrument proper.

15.4.11 Electric Controls

Both series and parallel hookups were tried for the three Edgerton lamps in each phototheodolite. Series operation gave consistent response, whereas the behavior of the parallel hookup was erratic. In a preliminary test, a 1 μf charge of 3,000 v direct current gave sufficient light for good photographs on Shellburst Panchromatic film. Since long 3,000-v lines running to the instrument were not desirable, the power pack was built into the instrument with a 110-v line entering at the control panel. Although the flashing of the lamps is to be controlled from a central station, a testing switch is included in the control panel of each instrument.

The camera solenoid is likewise controlled at the central station, but a test switch is also provided for use in threading the film.

In the event that the time counters in the two phototheodolites are out of synchronization, a pulsing switch is provided for actuating the counter in each instrument.

For cine operation of the camera (20 frames per second), a 60-c source at the central station is held in synchronism with the 10 pulses per second that go to the flash lamp. The 60-c line is provided with a rheostat and voltmeter, since the distances from the central station to each phototheodolite station will probably be different.

For night photography, suitable lamps are provided to illuminate the telescope cross hairs, and by a weak exposure to record the fiducial marks on the films. The night lamps are controlled by a switch on the panel.

15.4.12 Alignment of Instrument

Camera Reticle

If the vertical cross hair is made perpendicular to the horizontal camera axis, the horizontal cross hair will by construction be parallel to the horizontal axis. With the camera viewer in place, a distant point is sighted and the camera traversed in elevation. The reticle is then oriented until the vertical cross hair is parallel to the direction of motion of the sighting point. Since the reticle is fixed to the camera, the entire camera must be moved and then pinned into place after the adjusting operation.

Axes

The method employed for adjusting the perpendicularity of the horizontal and vertical axes is outlined in Section 15.4.9. Two con-

[redacted]

venient methods may be used to determine the amount of misalignment. The first is similar to the well-known surveyor's "high-low" test and differs only in that the error is actually evaluated. The instrument is first leveled on a solid foundation and azimuth and elevation readings are taken on two distant points, one at about 0-degree elevation and the other at about 45 degrees. The readings are then repeated with the instrument "dumped," or reversed. The following notation is employed:

a_1 = azimuth reading of low target with line of sight normal.

a_1' = azimuth reading of low target with instrument reversed.

e_1 = elevation reading of low target with line of sight normal.

e_1' = elevation reading of low target with line of sight reversed.

The subscript 2 denotes corresponding readings made on the high target.

Also, let

δ = angular misalignment of line of sight in a plane formed by the line of sight and the horizontal axis.

γ = angular misalignment of the horizontal axis with respect to the vertical axis.

From the geometry of the problem, the errors δ and γ are shown to be expressible in terms of the following equations.

$$\theta_1 \cos E_1 = \delta + \gamma \sin E_1, \tag{1}$$

$$\theta_2 \cos E_2 = \delta + \gamma \sin E_2, \tag{2}$$

where

$$\theta_1 = \frac{a_1' - a_1 - 3{,}200}{2}, \qquad E_1 = \frac{e_1 - e_1' + 3{,}200}{2},$$

$$\theta_2 = \frac{a_2' - a_2 - 3{,}200}{2}, \qquad E_2 = \frac{e_2 - e_2' + 3{,}200}{2}.$$

Equations (1) and (2), which are to be solved simultaneously for δ and γ, are valid only for small values of δ, γ, and θ. All the angles are expressed in mils.

A second method for determining the misalignment of the axes can be performed in the laboratory. The phototheodolite is placed on a solid foundation and brought into approximate level. An adjustable reticle is attached at each end of the horizontal axis and a filar microscope or cathetometer placed solidly on the same foundation and focused on each reticle. The center of each reticle is first adjusted until it coincides with the horizontal axis by observing its movement with the microscope as the horizontal axis is rotated through 3,200 mils (180 degrees). The microscope is adjusted vertically to the center of the second reticle, the amount of adjustment being a measure of the misalignment of the horizontal axis with respect to the vertical axis.

Lenses and Telescopes

The lenses must be oriented to the auxiliary ring so that the line of sight, which is formed by the nodal point of the lens and the intersection of the camera fiducial marks, is perpendicular to the horizontal axis. If the horizontal and vertical axes have been made perpendicular, sin E_1 in equation (1) above is zero and the misalignment δ of the line of sight follows directly from observation of a low target.

With the above adjustments accomplished, a distant target is sighted with the camera viewer and target lens, and the reticles in the tracking telescopes adjusted until both are centered on the target.

Elevation Zero

With the instrument leveled, a distant target just above the horizon is sighted and the elevation angle read. The instrument is then reversed and turned in azimuth until the target is again sighted. The elevation angles should be identical in both cases. If the readings differ, the elevation 0.1-mil drum is moved on its worm shaft, by means of a tangent screw, by half the difference between the two readings.

15.5 CENTRAL CONTROL STATION

The purpose of a central control station is to control the operations of the phototheodolites and auxiliary testing equipment, the latter to be used for collecting data from fire-control instruments under test with the phototheodolites.

As a result of meetings held at Aberdeen and Fort Bliss early in 1945, attended by representatives of the Services, NDRC, Eastman

Kodak Company, and Bell Telephone Laboratories, the following decisions were reached:

1. In view of the required testing of high-speed projectiles, the Edgerton flash illumination of the angle dials is to occur at the midpoint of the target exposure.

2. A controlling pulse generator, of an accuracy of 1 part in 100,000, is to send pulses to the camera solenoid, and an equally precise time delay is to send pulses to the Edgerton lamps after a predetermined time delay.

3. Data from equipment under test are to be collected by *data recorders*. These instruments, which are built by Bell Telephone Laboratories, translate selsyn data into printed numbers on tape.

15.5.1 Principles of Operation

Figure 14 is a schematic diagram of the control equipment. The station is controlled by a master oscillator, consisting of a crystal vibrating at 100,000 c. The oscillator is fed to six electronic decade counters, each of which counts the cycles, and at a preset number of beats sends out a pulse for activating other circuits. Thus, the combination of oscillator and electronic counters is capable of sending pulses through six separate circuits at any one of four desired frequencies, 1, 2.5, 5, or 10 c, with an accuracy of 0.00001 sec.

The pulse from counter 1 operates the solenoid circuit for the phototheodolite camera mechanism, and at the same time actuates a precision time delay that sends a pulse to flash the Edgerton lamps of each phototheodolite. Since the flashing of the lamp provides the primary time base, this time delay is supplied by an additional precision electronic counter.

The remaining five circuits operate the data recorders and other test equipment. The pulses to these circuits are controlled by frequency selector switches, which select pulses in phase with those sent to the phototheodolites. In each circuit a pulse is sent to a time-delay electronic counter, which is adjustable over a range of 1 sec, with a precision of 0.001 sec. After a preset delay, the pulse is passed on to a second time delay and then to the test equipment, and waits for another pulse. When four data recorders are being used, the selector switches for circuits 2, 3, 4, and 5 operate at 1 pulse per sec, and the time delays are set to operate the data recorders at interlocking intervals of ¼ sec. Every fifth pulse to the data recorders is used to produce an identification mark on the paper tape.

The outputs of circuits 2, 3, 4, 5, and 6 and of the fifth-pulse selectors are fed into a cross-connecting grid board which makes a flexible electric coupling between the various units. The output of the grid board feeds into a bank of twenty wet-reed mercury relays, precise to ± 0.001 sec, which distributes the load to the test equipment. These relays feed into a second cross-connecting grid board, whose output goes to four 19-plug connectors and subsequently to the phototheodolites and test equipment.

An additional unit supplies controlled 60-c current to run the phototheodolite camera motors in synchronism with the master oscillator. Thus, when the camera mechanism is operating at the motion-picture rate (20 frames per sec) it is in phase with the flashing of the Edgerton lamps.

15.5.2 Construction and Installation

The control equipment is installed in an Army maintenance truck containing a workbench and a motor-generator set with a 10-kw power output.

The master oscillator, time-delay units, fifth-pulse selector, and 60-c control unit for the camera mechanism were made by the Potter Instrument Company, Flushing, Long Island, New York. The cross-connecting grid boards, the relay rack, and installation of the entire unit were made by the Eastman Kodak Company.

15.6 INSTALLATION OF PHOTOTHEODOLITES

15.6.1 Location

The phototheodolites have been transferred to the Army Ground Forces Board No. 1, Antiaircraft Service Test Section, and at this writing are being permanently installed at Fort

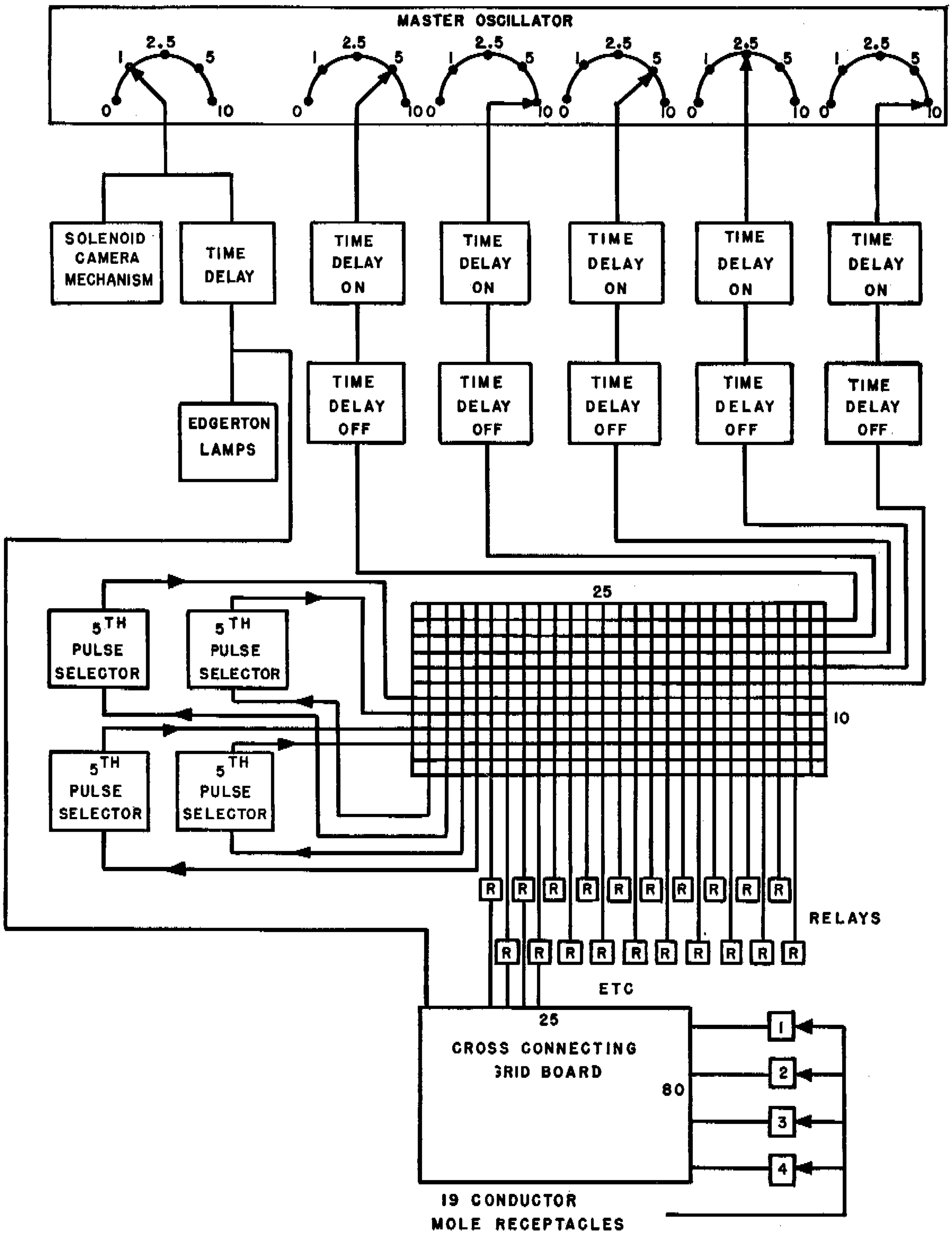


FIGURE 14. Central control unit for phototheodolite.

Bliss, Texas, under a direct Ordnance contract with Eastman.

15.6.2 Housing

A photograph of the general appearance of one of the two proposed phototheodolite instal-

FIGURE 15. Photograph of phototheodolite installation.

lations at Fort Bliss is shown in Figure 15 and an elevation in Figure 16. The phototheodolite rests on a reinforced concrete pier, which is isolated from the rest of the structure. A large, grillwork steel floor is supported by rollers 120 degrees apart. Attached to the floor is a *radome,* built of sponge rubber reinforced by hardwood ribs and sprayed with Fiberglas both inside and out. The dome slit is adjustable from the top, and will not open beyond the required elevation angle.

15.6.3 Tracking for Housings

Provision has been made for automatic following of the dome. Attached to the phototheodolite is a movable arm that carries a carbon brush contact. The contact mates with a variable-resistance sector, which is attached to the base of the housing and which is in turn connected to a motor that drives a selsyn transmitter. The selsyn receiver drives an oil gear connected to one of the three wheels that support the superstructure.

15.6.4 Electrical

The electric connections between each phototheodolite station and the central control station will be provided by bare copper wires

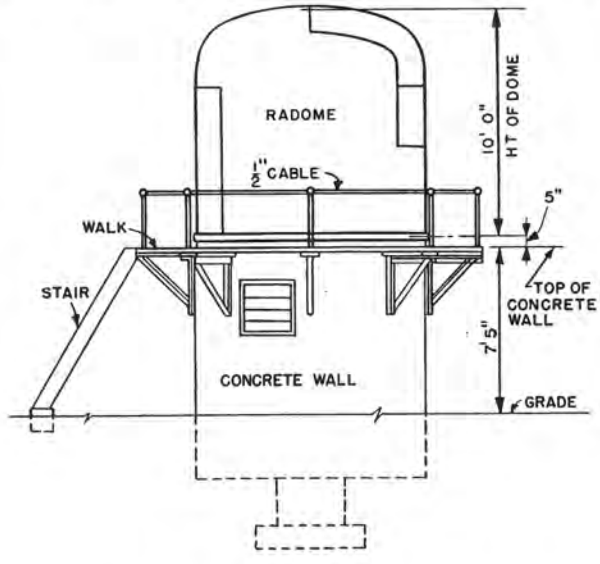


FIGURE 16. Diagram of phototheodolite installation.

strung on telephone poles between the two stations. Terminal boxes will be constructed at various points on the base line for the purpose of running the controls from the central station to the phototheodolite stations.

15.7 TESTING OF THE PHOTOTHEODOLITES

15.7.1 Preliminary Test of Azimuth Worm Wheel

A preliminary test of the two azimuth worm wheels was conducted at Gould and Eberhardt after assembly of the worms and worm wheels.[1a]

A Zeiss theodolite was employed, with a collimator placed at one end of the test room serving as a target. Readings were made for every 400 mils rotation of the phototheodolite, in both clockwise and counterclockwise directions, but with only one orientation of the phototheodolite with respect to the theodolite. The worm-wheel errors were found to be periodic, the amplitudes averaging about 0.030 mil for the No. 1 instrument and about 0.020 mil for the No. 2 instrument.

15.8 RECOMMENDATIONS BY NDRC

15.8.1 Proposed Tests

Performance tests of the phototheodolite had not been carried out when the contract was terminated. NDRC has proposed the following series of tests to be made by the U. S. Army.

Test of Photographic Resolving Power of Each Lens

Exposures of three-parallel-line targets (white on black) are to be made at close intervals running through focus on Super-XX film processed in D-19 for 8 min at 68 F. The targets can be located either (1) at finite distance equal to at least fifty times the focal length of each lens or (2) at the focus of a 30-ft focal length, 22-in. diameter concave mirror loaned by Mount Wilson Observatory to Eastman Kodak Company.

Static Tests

This test is to determine if the phototheodolite indicates the same azimuth and elevation bearings of a target when the target is approached from four directions.

Targets may be (1) black-on-white cross at 11,000 yd in daytime, (2) electric lamp at 11,000 yd at night, (3) the moon in daytime, or (4) stars at night (at least 20 degrees elevation). Photographic tests have shown that sixth magnitude stars give adequate density on Shellburst Panchromatic film, with a 48-in. $f/5$ lens, with 1-sec exposure made by removing a cardboard shutter by hand. Best results will be obtained by using third or fourth magnitude stars. Exposures on the moon or stars must be timed by Bureau of Standards time signals on a loudspeaker or by a good watch or chronograph.

Approach target from each of four directions (U, D, R, L), with phototheodolite *stationary*. Make exposures of target. Compare apparent azimuth and elevation for U, D, R, L approaches.

To calculate azimuth and elevation of stars and moon, use the following formulas:[b]

elevation

$$\text{hav}\,(90^\circ - H) = \text{hav}\,(L \sim d) + \cos L \cos d \,\text{hav}\, t,$$

azimuth

$$\sin Z = \sin t \cos d \sec H,$$

where

H = elevation of star,
L = latitude of station,
d = declination of star,
t = meridian angle of star,
Z = azimuth of star.

The above formula for azimuth is based on the assumption that the elevation has already been computed. Near the zenith this formula is indeterminate.

If it is desired to compute azimuth, without having previously computed elevation, the following formulas may be used:

$$\tan \tfrac{1}{2}\,(Z - A) = \cot \tfrac{1}{2}\,t \sin \tfrac{1}{2}\,(L - d) \sec \tfrac{1}{2}\,(L + d),$$

$$\tan \tfrac{1}{2}\,(Z + A) = \cot \tfrac{1}{2}\,t \cos \tfrac{1}{2}\,(L - d) \operatorname{cosec} \tfrac{1}{2}\,(L + d),$$

where A is the angle subtended, at the star, between the zenith and the pole. After computing $Z - A$ and $Z + A$, A is eliminated by adding the two equations.

Dynamic Tests

This test is to determine whether the phototheodolite is sufficiently free from deflection to indicate the same azimuth and elevation bearings of a target when the target is approached

[b] 1. For sign convention $(L \sim d)$, see Dutton, Navigation and Nautical Astronomy, p. 266.
2. For table of haversines, see Bowditch, American Practical Navigation Table 34, 1938.
3. Elevations should be corrected for refraction.
4. The formula for azimuth will be satisfied by two values of Z, differing by 180 degrees, but the correct value will be obvious.

[redacted]

from four directions at slow, medium, and fast speeds.

Targets may be the same as those used in the static tests except that, in the case of stars, 0.0 to 1.0 magnitude stars should be used in order to give adequate density for cine operation which is an exposure time of 0.01 sec. Bureau of Standards time signals can be used to start cine operation.

Track at slow, medium, and fast speeds past target, using cine operation of camera. Compare apparent azimuth and elevation for each speed.

Overall Static Tests

This is to determine the overall accuracy of the phototheodolite in a static condition at various points evenly spaced around the azimuth and elevation scales.

Stars are probably the most convenient targets, ten or twelve stars preferably about third or fourth magnitude, distributed reasonably uniformly over the sky and all at more than 20 degrees elevation, would be sufficient.

Track phototheodolite onto each star and take an exposure of 0.5 to 1 sec by manual removal of cardboard shutter. Compare apparent azimuth and elevation bearings with calculated values of the stars.

Overall Dynamic Tests

This test is to indicate the overall accuracy of the phototheodolite as in the static tests except under dynamic conditions of slow, medium, and fast tracking speeds past the stars.

Ten or twelve stars of 0.0 to 1.0 magnitude, distributed reasonably uniformly over the sky all above 20 degrees elevation would be sufficient.

Track phototheodolite onto each star at slow, medium, and fast speed using cine operation of camera. Compare observed azimuth and elevation with calculated values of the stars.

Test for Periodic Error in Worms

Track a third or fourth magnitude star (above 20 degrees elevation) at night, and the moon in daytime, at considerable distance from the meridian (so that both azimuth and elevation are changing).

Make 0.5- to 1.0-sec exposures on a star at night at intervals of 30 sec, during a period of 30 min. In the daytime make short cine runs on the moon at 30-sec intervals, to permit single frame exposures (about 0.5 sec) by removing cardboard by hand.

Time the exposures with Bureau of Standards time signals or with chronograph.

Plot errors to detect any periodic error in azimuth or elevation worms.

15.8.2 Recommended Design Changes

1. Three differential screws may be used to align the horizontal and vertical axes, provided the base of the upper casting is strengthened so that the uprights do not toe in or out.

2. Because it is desirable to grind the bearing seats on the horizontal axis after the axis assembly is complete, the camera housing should be strengthened so that it has the same stiffness in all radial planes.

3. For convenience in assembly, the upper casting should be so constructed that the elevation worm and worm wheel can be removed without raising the horizontal axis out of its bearing seats.

4. The instrument should be balanced about the vertical axis to reduce strain on the base casting. The base casting should be further strengthened, and steel inserts with an acme thread provided for the leveling screws.

5. The design of oil-drip pans for the worm wheels should be improved.

6. The large castings should be redesigned to make more accessible the dials, chain drives, optics, etc.

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Chapter 16

OPTICAL SCANNING DEVICES

By *Theodore Dunham, Jr.*[a]

THE EFFICIENCY of lookouts in detecting aircraft from land stations and in detecting both aircraft and submarines at sea is of paramount importance. The loss of even a few seconds in detecting the approach of enemy aircraft or submarines may have a disastrous effect on the outcome of an engagement. Whatever optical aids improve the performance of lookouts, by even a small percentage, justify full study and development.

The use of hand-held binoculars for increasing the range at which targets can be detected, both by day and by night, has become universal. Studies aimed at establishing the characteristics of night binoculars which will increase their efficiency to the maximum that is possible with hand-held instruments are described in Chapter 5.

There are two obvious drawbacks associated with the use of hand-held binoculars. In the first place the field is necessarily limited (7.3 degrees in the case of the standard 7x50 binocular) when a magnifying system is used. This means that the observer must sweep in one coordinate when searching for submarines and in two coordinates when covering a sector of the sky while searching for aircraft. In the second place, the observer rapidly becomes tired, even under the best conditions, so that his efficiency as a lookout inevitably falls off after the first few minutes. Under adverse conditions, such as wind and cold, the efficiency of any lookout is reduced much further. Anything that can be done to lessen the fatigue and increase the comfort of a lookout will markedly better his performance in detecting distant targets at the limit of visibility and will extend the period of time during which he operates efficiently. This is an important consideration and should be given serious attention.

The development of optical and mechanical aids for scanning the horizon and the sky was given attention by Section D-3 of NDRC, beginning early in 1941. The work was continued under Section 16.1 (after 1942, Project 16.1-4) and although it was never given high priority and never aroused much interest in the Services, several experimental devices were developed and tested in a preliminary fashion.

[a] Chief, Section 16.1, NDRC.

16.1 REQUIREMENTS OF A SATISFACTORY SCANNING DEVICE

Although the requirements of a scanning device depend to a considerable extent on the particular application for which it is intended, there are several requirements which apply in general.

1. The observer should look directly forward at all times and should if possible be comfortably seated and protected from the wind. It should be unnecessary for him to turn his head to follow the changing direction of the field which he is examining. The change in direction should be accomplished, whenever it amounts to more than a small angle, by the rotation of one or more reflecting devices ahead of the eyepiece. When the angle to be covered is small, it may be satisfactory to turn the whole instrument, including the eyepieces, but if this is done the center of rotation should preferably be close to the eye so that the observer can follow the device almost entirely by turning his head, with a minimum of side motion. A third alternative is to mount the observer and his instrument on a platform which turns as a whole, and which can be stabilized if necessary. This is to be avoided, whenever possible, since it requires more space than will usually be available.
2. The image must be maintained erect, and should not be turned right-for-left. Even when scanning for aircraft, this is important because if a target is spotted it is essential to get the correct interpretation of what the observer sees as quickly as possible.
3. Vibration must be eliminated as far as possible. Linear vibration is not particularly serious if it is not excessive, but oscillation in angle must be reduced to a minimum if the full advantage of magnification is to be realized. The human frame is remarkably efficient as a vibration and oscillation eliminator and if it is to be replaced by a mechanical mounting for the scanning device then special care must be taken with the design.
4. Provision should be made, particularly in the case of devices intended for use in scanning for aircraft, for

scanning the area under observation either manually or automatically. A careful comparison will be required to determine which method is most efficient.

5. When automatic scanning is employed, the change from one field to another may be made either gradually, by a uniform motion of the whole device or of the reflectors within it, or it may be made by sudden jumps from one field to another, with pauses lasting long enough to permit examination of each field. Experiments, under conditions simulating those encountered in practice, will be required to choose between these two types of scanning programs. If intermittent scanning is employed, it may be necessary to incorporate a shutter in the system to prevent the observer from being disturbed by seeing the field jump between successive periods of rest.

6. There may be important practical advantages in scanning devices which employ standard binoculars, with external equipment to produce the scanning effect. Such a design will usually be simpler and will involve a less serious problem in production than will a device which is special throughout. On the other hand, a composite instrument, consisting of standard binoculars and auxiliary scanning equipment, is almost certain to absorb more light than would a device specially designed to combine the optical and the mechanical functions. At night this consideration is more important than in the daytime.

16.2 PRINCIPLES OF OPTICAL AND MECHANICAL DESIGN

The purpose of the scanning devices developed under NDRC was to permit the observer to cover the sector assigned to him in systematic fashion by employing mechanical and optical means to change the direction of his view while he looks always in a fixed direction into monocular or binocular eyepieces. It was hoped that such a device would lead not only to a more systematic coverage of the assigned sector, but would also appreciably increase the comfort and hence the efficiency of the lookout.

All the scanning devices described depend on the rotation of one or more plane mirrors or prisms which are incorporated in the optical path. The usual erecting system used with telescopes requires four reflections—two in each of two planes at right angles to one another. Several scanning devices are based on rotating one or more of these mirrors. In some devices additional mirrors are added expressly for the purpose of scanning, for example, when a standard binocular with its built-in erecting system is used. The optical design of the panoramic telescope, which is widely used for controlling the fire of field guns, has been used in one scanner. Several more complex systems have been devised and models of some have been made. Obviously, there must be an even number of reflections, usually four or six, to preserve the right-left orientation of the field when the image is erect.

The present designation of individual scanning devices is by no means satisfactory. The names used most commonly by those who developed the devices and which are in OSRD reports have been retained with the full realization that a more logical nomenclature is needed.

16.3 INDIVIDUAL SCANNING DEVICES

A systematic study of possible designs for scanning devices was made at the Mount Wilson Observatory[1] under Contract OEMsr-101. The Yerkes Observatory[2] under Contract OEMsr-1078 developed a panoramic scanner and built a model for testing.

16.3.1 Double Dove Prism Scanner

The first scanning device to be constructed and tested at Mount Wilson[3] employed a pair of double Dove prisms mounted in front of the objectives of an 8x56 binocular, linked together and driven by an intermittent mechanism which served to bring into the observer's view successive fields of view along the horizon, spaced 5 degrees apart. A device of this kind might be entirely practical for horizon scanning, but since it has no provision for vertical scanning it would be necessary to stabilize the Dove prisms and the binocular. The device was developed primarily for experimental purposes to determine the optimum period of rest and the optimum angular spacing of successive fields for horizon scanning. A model was made, but time did not permit completing the program of testing.

16.3.2 Panoramic Scanner

A model of this device was made in monocular form at the Yerkes Observatory.[2] It displays an erect image of a target and covers the entire sky. It is based on the standard military panoramic telescope. A double Dove prism directs light from a target at any elevation vertically downward, through the objective and through a Schmidt rotating prism in the converging beam, to a roof prism which turns the beam horizontally to the eyepiece. The Schmidt prism is geared to turn at one-half the rate at which the double Dove prism turns in azimuth, and serves to compensate the rotation of the field which would otherwise occur. The telescope system is a 10x50 wide-field 7-degree design developed at the University of Rochester.[4] Figure 1 shows the optical layout of the reflecting elements and Figure 2 shows a photograph of the complete instrument. False reflections were eliminated by cementing plane-parallel plates with beveled and blackened edges to the faces of the double Dove prism and by mounting curtains at the sides (for details see the Yerkes Observatory Report[2]). Scanning in elevation is controlled by two hand wheels on a horizontal axis, while scanning in azimuth is accomplished by rotating the entire upper assembly about a vertical axis by means of the same handles or by turning a large knurled nut surrounding the base of this assembly.

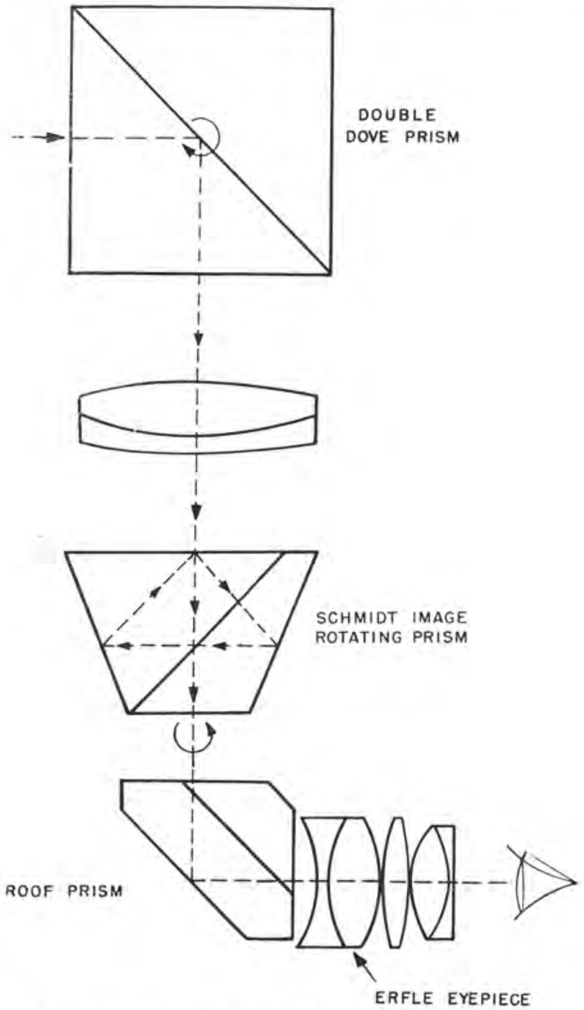

FIGURE 1. Optical system of panoramic scanner.

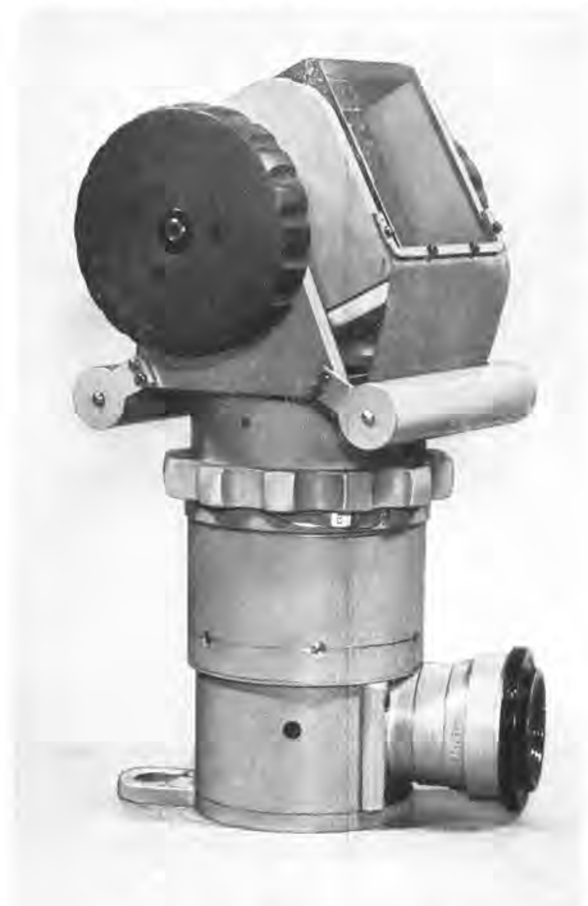

FIGURE 2. Panoramic scanner.

The Dove prism must be made to close specifications to avoid doubling of the image, and it has the further disadvantage that it absorbs

a considerable amount of light. A rear-surfaced mirror might well be substituted for the Dove prism. Such a mirror need not be inconveniently long, since it may not be necessary to scan the sky up to the zenith, and in any case it is probably unnecessary to fill more than about half the aperture at the maximum elevation. If a mirror were used, it would probably be

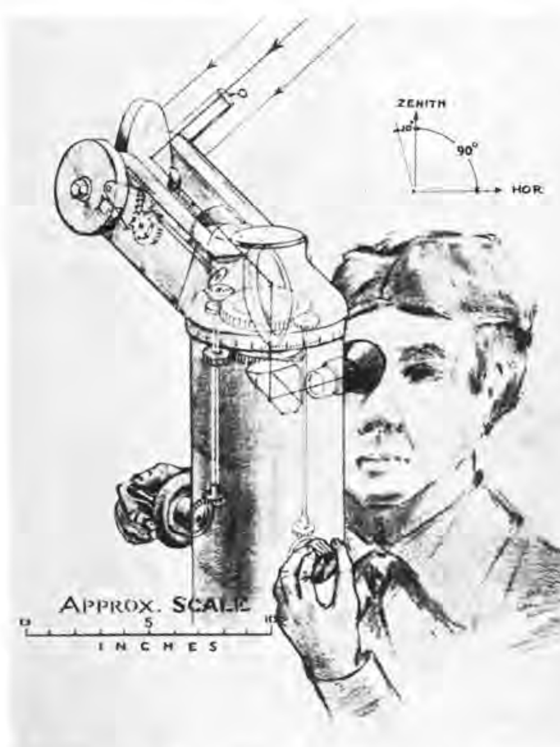

FIGURE 3. Altazimuth two-mirror scanner.

practical to design a binocular device with a single mirror large enough to cover the two objectives. The principal problem would be that of holding the dimensions of the two image-rotating prisms and their cells within small enough limits of size so that they would not interfere with one another when their centers are separated by only about 65 mm.

The panoramic scanner is one of the most compact and generally satisfactory designs that have been investigated. Limited tests have shown that the device is capable of convenient and efficient operation. If provided with detents, for setting at specified intervals in elevation, it can be used to cover systematically any desired portion of the sky by sweeping in azimuth at each setting in elevation. Circles can be added for reading the coordinates of a target.

16.3.3 Altazimuth Two-Mirror Scanner

The design of this device[1a] resembles that of the panoramic scanner in many respects, except that the rotating Schmidt prism is omitted and that two plane mirrors, one fixed and one adjustable, replace the double Dove prism. The objective is placed between the two mirrors. The entire sky can be covered, but the field rotates when the setting in azimuth is changed.

The arrangement of optical parts and the mechanical controls are shown in the phantom sketch in Figure 3. The first mirror is located above the second mirror, separated by an amount which is sufficient to permit reaching the horizon without interference. Some reduction in aperture is tolerated at the zenith in order to avoid excessive length of the first mirror. The setting in elevation is controlled by a knob turned by the left hand which changes the setting of the first mirror. Scanning in azimuth is accomplished by turning a crank handle, operated with the right hand, which rotates the upper assembly consisting of the two mirrors and the objective. The two controls are linked together through a cam, so that when desired the setting in elevation starts at 90 degrees and falls continuously to 0 degrees after approximately sixteen complete revolutions in azimuth. The setting then returns to the zenith through the action of a spring released by the cam. Thus the entire sky is covered systematically. A motor could be used to provide continuous drive in azimuth. This might well be arranged to run at a faster rate near the zenith where the circular paths to be covered are much smaller than near the horizon.

In accordance with usual definitions, the altazimuth two-mirror scanner causes rotation of the field of view, that is, the apparent direction of the horizon line rotates steadily in the field as the instrument scans in azimuth. Although this would undoubtedly be a serious disadvantage in an instrument intended for searching for submarines close to the horizon, it may not be at all disadvantageous when

searching the sky for aircraft, since efficiency in detecting targets in an otherwise clear sky field is not likely to depend on the orientation of the field. The presentation with this scanner is actually exactly as it would be if the observer were lying on his back looking up at the whole sky and were to imagine it flattened into a large disk, except that the roof prism turns this presentation through 90 degrees, so that it is seen by looking horizontally instead of vertically. The first mirror brings areas in any part of the sky into the line of sight (actually into the zenith, apparently to the horizon due to the roof prism) without rotating these areas. It may be that this presentation would be as satisfactory in practice as any other that could be devised, particularly if a device were added to indicate not only the part of the field of view toward which the device is directed, but also the direction within the field of a line parallel to the horizon. This could easily be done in the case of the present monocular device by allowing the inactive eye to watch at will a disk representing the entire flattened sky, upon which a short straight line would be located at a point corresponding to the elevation and azimuth of the center of the field of the instrument at the moment. The reference line would be mounted perpendicular to a radial arm on the sky disk, and so would always indicate the direction in the field of a line parallel to the horizon. This information would facilitate reporting the direction of motion of the targets detected with the scanner. If it should prove desirable to prevent rotation of the field, this could of course be done by adding a Schmidt prism, linked at half speed, to the rotation in azimuth, similar to that used in the panoramic scanner.

As in the case of other monocular scanners, a binocular rubber eyecup should be added to aid the observer in locating and maintaining his eye in the proper position and to reduce fatigue. The view of the inactive eye should be blocked, either with an opaque diaphragm or, perhaps better, with a ground glass illuminated with reflected sky light to present to the inactive eye an area having approximately the same brightness as the sky. Experiments might well be carried out to determine whether a comfortable headrest and eye guard would improve performance and reduce fatigue.

The altazimuth two-mirror scanner was originally intended for use in scanning for aircraft at shore stations, but it could be used almost equally well in scanning for aircraft on shipboard. It could probably be stabilized more easily than most of the other scanners described in this chapter by linking the vertical axis to a damped gyro pendulum and by providing the roof prism with a half-speed motion, about a transverse axis, with relation to the same pendulum.

Only limited field tests have been made with the present model. Observers found the controls somewhat inconvenient to operate, largely because the rate of response in elevation was too slow. They regarded monocular instruments as inferior to binocular instruments, and criticized the rotation of the field. It seems likely that most, if not all, of these criticisms can be overcome or shown not to be serious.

The comparative simplicity of the altazimuth scanner and the fact that it covers the entire sky makes it seem desirable that further development be carried out to investigate fully its capabilities after indicated improvements have been made.

16.3.4 Porro System Scanner

The changes in direction of the line of sight which are required for scanning may be achieved by rotating one or more of the reflectors that are used for erecting the image in a telescope system. It is well known that four 90-degree reflections from plane mirrors properly oriented can invert an optical image while maintaining the original direction of the beam. No two reflectors may be parallel to one another; if they are, their effects cancel.

At each reflection the incident and reflected rays define a plane of reflection. In an erecting system two different arrangements are possible. In one the first and second planes of reflection may coincide, while the third and fourth also coincide. These two planes must be perpendicular to one another and they must intersect along the ray which passes between the

second and third reflectors. This arrangement is similar to Porro prisms of Type I. Alternatively, the second and third planes of reflection may coincide. In that case this plane must be perpendicular both to the first and to the fourth plane of reflection. The two lines of intersection formed by these planes are the rays which pass between the first and second reflectors and between the third and fourth reflectors respectively. This arrangement is similar to Porro prisms of Type II.

Scanning devices may be based on any of the numerous systems which fulfill these conditions, provided one or more of the reflectors are mounted on axes around which they can be rotated. To prevent the image from rotating in the field of view, it is a necessary and sufficient condition that the axis on which each reflector turns shall lie in the plane of that reflector, and perpendicular to the plane defined by incident and reflected rays at the center of the field.

Reflections in the various directions may follow one another in any sequence which is convenient for a given application.

In a simple optical system which is intended for scanning, and in which the final beam is to lie parallel to the incident beam, we may, for convenience in description, assume that the object is north (N) of the observer. Then the beam travels south (S) and will first be reflected 90 degrees, either upward (U), to the east (E), downward (D), or to the west (W). The second reflection may turn it 90 degrees in any one of the three standard directions (including N and S, as well as U, E, D, and W) which do not involve placing the second reflector parallel to the first. The third reflection may turn the beam 90 degrees in either one of the two directions still permitted. The direction of the fourth reflection is uniquely defined, since it must turn the beam in the same direction (S) as the incident beam.

Table 1 lists the sixteen possible sequences in which the four reflections may be arranged.

Each of these arrangements corresponds to a Porro prism system of Type I or Type II. The Porro type is indicated in the last column of the table. In Type I the first and second reflections lie in the same plane, while the third and fourth reflections lie in a common plane at right angles to the first. These two planes are at right angles to one another and both are parallel to the N-S line. In Type II the second and third reflections lie in a common plane perpendicular to the N-S line, while the first and second reflections lie in separate planes, parallel to one another and to the N-S line. The eight variations of each type are merely the result of changing the order in which the different reflections follow one another and of the fact that there is a right-handed and a left-handed version of each arrangement.

TABLE 1

Type	Sequence	Porro prism type
1	S→U→N→W→S	I
2	S→U→N→E→S	I
3	S→U→W→D→S	II
4	S→U→E→D→S	II
5	S→W→N→D→S	I
6	S→W→N→U→S	I
7	S→W→D→E→S	II
8	S→W→U→E→S	II
9	S→D→N→E→S	I
10	S→D→N→W→S	I
11	S→D→E→U→S	II
12	S→D→W→U→S	II
13	S→E→N→U→S	I
14	S→E→N→D→S	I
15	S→E→U→W→S	II
16	S→E→D→W→S	II

These sixteen optical arrangements are illustrated in Figure 4, which may be useful in selecting the most suitable system for a specific application.

The objective may be located anywhere in the system—ahead of the first mirror, between any two mirrors, or following the last mirror. The eyepiece must, of course, follow the last mirror.

In order to change the line of sight for scanning, any one of the reflectors may be rotated around an axis which lies in its own plane and perpendicular to the plane defined by the incident and reflected rays. When this is done, all parts of the system which lie between the swinging reflector and the object must rotate as a unit on the same axis and at twice the speed of rotation of the reflector. Rotation may be provided for one, two, three, or for all four of the reflectors. Each reflector may be either a totally

[redacted]

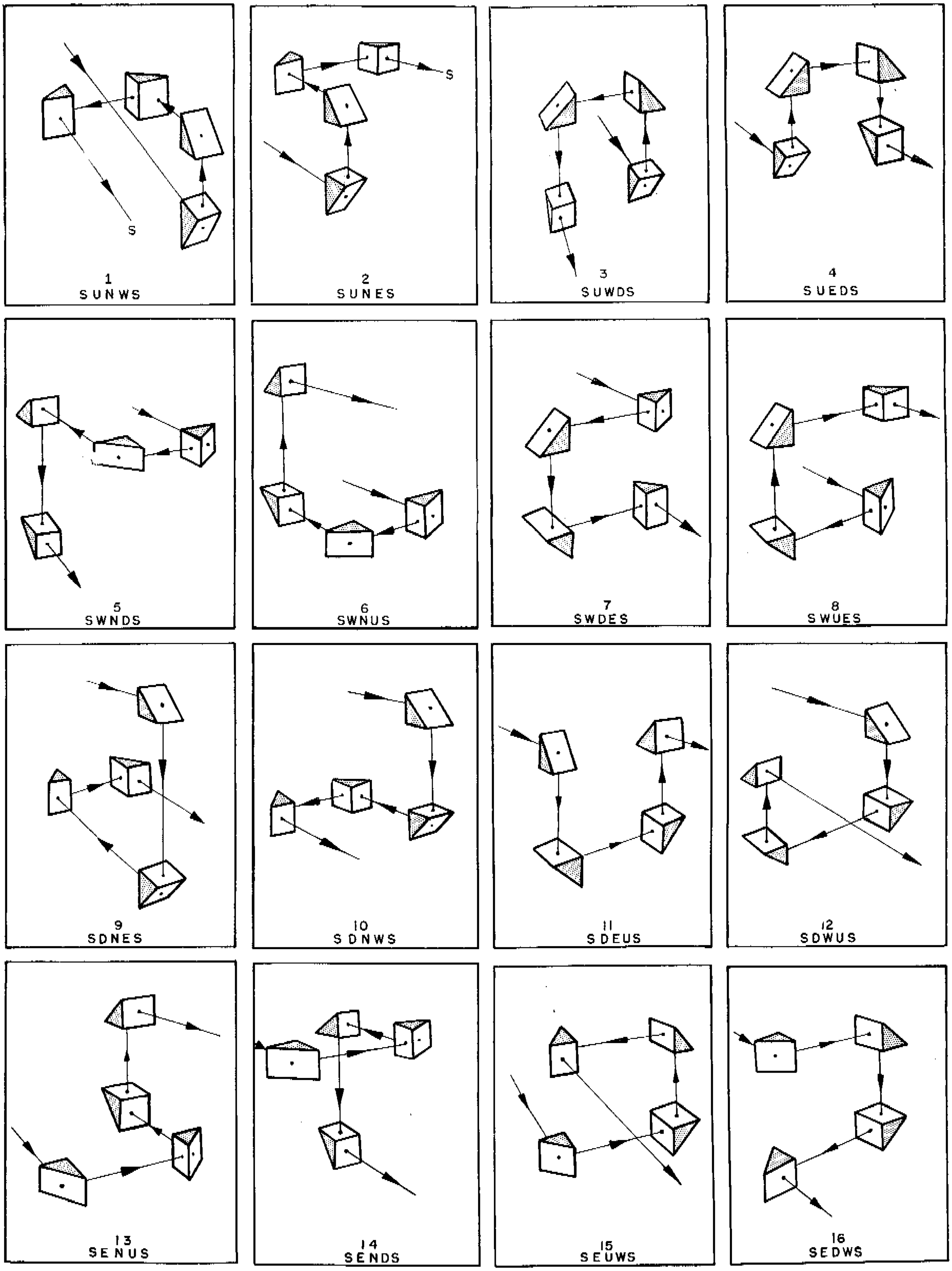

FIGURE 4. Porro erecting systems.

[redacted]

reflecting prism or a plane mirror. Two or even three reflections may be combined in a single glass prism.

Prisms have certain advantages, as compared with mirrors. They are more efficient and, when rotated for scanning purposes, they need not be nearly so long on their hypotenuse face as a mirror must be in order to give the same angular displacement of the beam. Also, they present no questions such as tarnishing in salt air. But they cannot easily be obtained in large sizes. Above 2 or 3 in. of aperture mirrors must ordinarily be used.

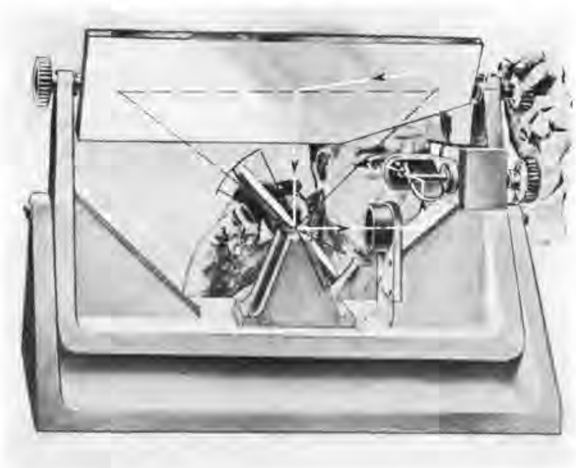

FIGURE 5. Mockup of Porro system scanner based on Type 12 of Figure 4.

The greatest angular sweep in two coordinates can be achieved by making all four angles flexible in the system. Type 6 for the right eye and type 13 for the left eye are probably the most suitable systems for such a design. The objective, in each case, would probably be placed between the second and third reflectors. All reflectors would presumably be prisms. It would be essential to maintain parallel, within close tolerances, corresponding arms in the two systems. This would not be as difficult as it might at first appear. The first and second reflectors need not be held in register with extreme accuracy, since the eye has appreciable lateral accommodation. The third and fourth reflectors, which control vertical register, must be coordinated more accurately, but this might not be at all difficult because corresponding arms in the right and left units move strictly together, and they could be rigidly tied to one another by means of right- and left-threaded rods which would also serve to adjust the interocular distance and to mount the whole device on its base. The possibilities of such a design should be studied in detail. A fundamental requirement is the design of an accurate, but simple, optical elbow with half-speed rotation of its self-contained prism.

The other optical arrangement which may be of considerable interest is type 12 for the right eye and type 11 for the left eye. Considerable angles can be covered in two coordinates by the first and second mirrors, both of whose axes can be mounted on the base of the instrument. The third and fourth reflectors can be prisms, which might be combined in a single piece of glass. The objective would be located between the second and third reflectors. It is necessary to make the first mirror very wide if more than a 60-degree total angle is to be covered in azimuth, but for moderate angles its size will not be excessive. A reasonably compact scanning device intended for covering moderate angles can almost certainly be made, based on types 12 and 11.

A preliminary model[1b] of a monocular scanner based on type 12 is shown in Figure 5. Vertical scanning is accomplished entirely with the first mirror, and horizontal scanning entirely with the second. About 115 degrees can be covered vertically and 90 degrees in azimuth. The addition of a similar system for the other eye would provide binocular vision without great additional complication.

When the instrument is in the position shown, the center of the useful range is somewhat below the horizon. Provision is made, however, for turning the first three mirrors as a unit about a horizontal axis through the fourth mirror. Readjustment of the fourth mirror and of the eyepiece then permits the vertical range to be changed so that it includes both the horizon and the zenith. The axis of the eyepiece can remain horizontal. These motions, which are incorporated in the present model only as adjustments, might be linked together with the proper relative speeds so that they would be available for actual scanning. This

would permit vertical scanning over a much greater range.

With this instrument there is no rotation of field in the usual sense, but the perspective is handled by the device in a way which may prove somewhat disturbing. This is much improved if the design is based on a Porro type which permits the first mirror to turn on a

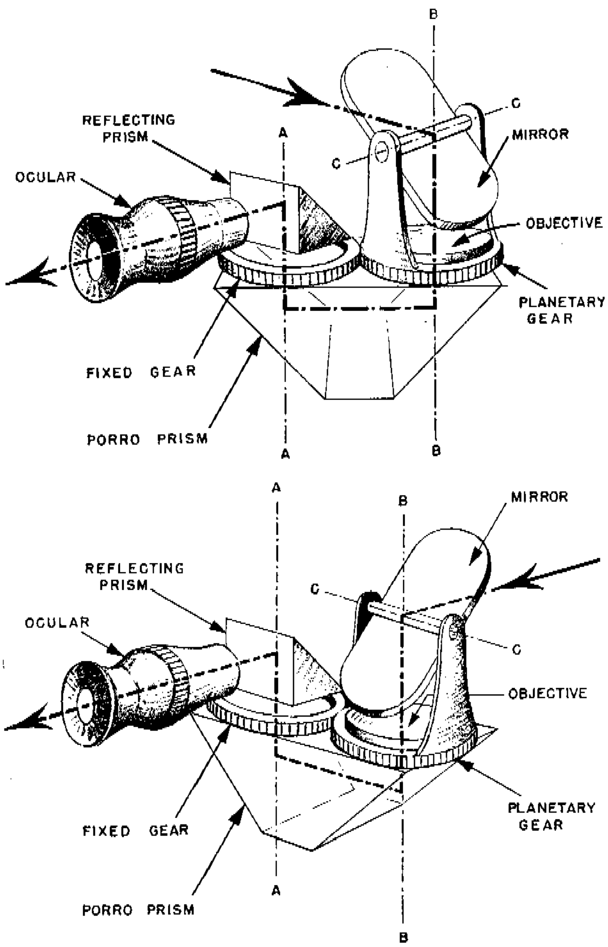

FIGURE 6. Altazimuth four-mirror scanner.

vertical axis, and the second mirror on a horizontal axis, but such an arrangement is less well adapted to binocular use.

16.3.5 Altazimuth Four-Mirror Scanner

This device[1c] is illustrated schematically in Figure 6. Four reflectors are employed and arranged in the neutral scanning position, in the same way as in the Porro system scanner (Figure 5). Referring to Figure 4, Type 12 is the system used for the right eye and Type 11 for the left eye. The first three mirrors rotate as a unit about a vertical axis, indicated by *A-A* in Figure 6, which passes through the centers of the third and fourth mirrors. In addition, the first mirror rotates about a vertical axis joining the centers of the first and second mirrors *(B-B)*, at twice the rate at which the first three mirrors rotate as a unit. Simultaneous rotation, at 2/1 speed, about these two vertical axes, provides horizontal scanning, and eliminates rotation of the field of view. The first mirror is mounted on a horizontal axis *(C-C)* to provide vertical scanning.

If the first reflector is a mirror, it will probably be difficult to carry vertical scanning more than about 60 to 70 degrees above the horizon, even if some reduction in aperture is allowed, since near the zenith the length of this mirror would become excessive. Actually, it may develop that it is unnecessary to carry scanning close to the zenith when the primary purpose is to detect approaching aircraft.

The second and third reflectors in this device can probably be combined in a single Porro prism (light entering and leaving through the hypotenuse face). For the fourth reflector, a right-angle prism will probably be used next to the eyepiece. The objective can be located between the first and second reflectors, thus keeping the first mirror as short as possible and permitting the combining of the second and third reflectors into a single Porro prism. This design involves less glass between the objective and eyepiece than does a standard binocular and it can therefore be employed effectively with wide-angle systems.

Preliminary studies indicate that this design is practical, both as a monocular and as a binocular. In a binocular design, the necessary linking of motions for the two eyes is not likely to present serious difficulty.

A monocular scanner of this type might be well adapted for use by the rear gunner in a bomber to detect the approach of fighter aircraft. The device can probably cover a range of about 180 degrees horizontally and about 120 degrees vertically (60 degrees above and be-

low the horizon) without exceeding the limits of a reasonably compact unit. Moreover, since a monocular device designed for the right eye would occupy space principally to the right of and below this eye, it would be easy to get an unobstructed direct view by merely displacing the head 2 or 3 in. to the left.

On ships, this scanner (in either monocular or binocular form) would be particularly satisfactory for scanning the horizon, because it does not rotate the field and because its construction is relatively simple. It can also be used for sky scanning whenever it is not necessary to cover a region more than 60 or 70 degrees above the horizon. Double Dove prisms, although somewhat objectionable, permit scanning to the zenith.

16.3.6 Aircraft Scanning Chair

This is one of the simplest designs[1d] and is intended for quick production to meet the need for a device to aid lookouts on naval and merchant ships in searching the sky. The optical system consists of a pair of standard 7x50 binoculars mounted so that the observer looks steadily into them along a line inclined upward by about 10 degrees. Light is brought to the objectives of the binoculars by two plane mirrors. The first mirror is carried on an arm which is pivoted at the second mirror (see Figure 7). Both mirrors rotate about axes perpendicular to the plane defined by the incident and reflected beams of light and are controlled by a suitable linkage. In this way, the dimensions of the mirrors are entirely reasonable. The mirrors provide vertical scanning. The entire optical system is mounted on the chair in which the observer is seated. The latter is carried on a vertical axis on ball bearings, which provides horizontal scanning when the observer causes it to rotate by pressure with his feet on the floor or deck. There is of course no rotation of the field of view.

Figure 7 shows a model of this scanning device. All optical parts are enclosed in a metal housing with two selected plate-glass windows, beveled at the edges, where they are in contact, and treated with low-reflection coating to reduce the intensity of reflections from the ground which may otherwise be troublesome under certain conditions of lighting. The binocular is mounted on one of the antioscillation mounts developed by the Eastman Kodak Company under Contract OEMsr-392 (see Chapter

FIGURE 7. Aircraft scanning chair.

14). The cutaway drawing in Figure 8 shows the arrangement of optical and mechanical parts.

Tests of this device, both on land and on a small vessel, show that it is entirely practical. Observers tend to favor this scanner above all of the other models so far developed, principally because of its simplicity, ease of operation, the comfort of the operator, and the fact that it provides binocular vision. Although developed primarily to meet the need for scanning at sea, it is equally well adapted for scanning for aircraft at land stations.

10.3.7 Rolling Cylinder Scanner

This device [1e] was developed at Mount Wilson to provide coverage over a wide area of sky without rotation of the image. While it is probably too complicated and the requirements relating to adjustment of mirrors may be too exacting to make it entirely practical, a brief description is included here, partly because the design is decidedly ingenious and partly because it is needed to complete the description of all designs for which models were actually constructed.

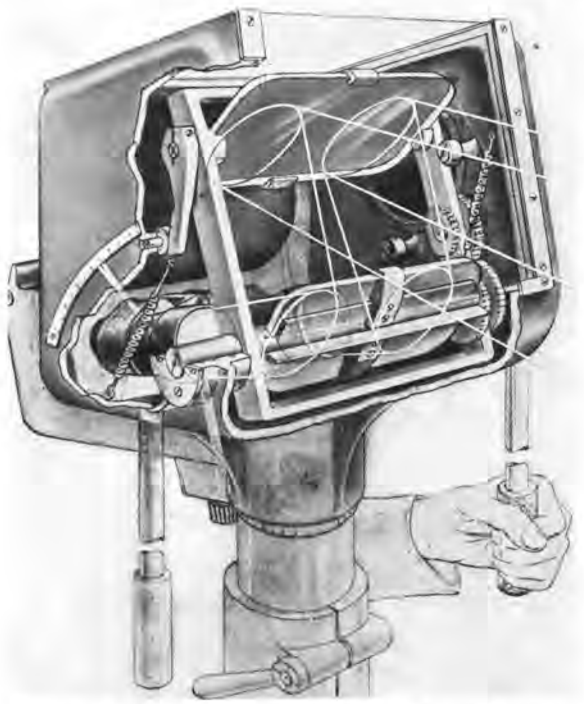

FIGURE 8. Constructional details of aircraft scanning chair.

The optical layout is shown in Figure 9. Light from the target falls on a flat mirror which directs the beam horizontally through the objective to an image-erecting system consisting of three mirrors, and then to a prism in which two 90-degree reflections occur. The beam emerges horizontally in a direction at right angles to the axis of the objective and finally passes to the eyepiece. There are six reflections in all. Two independent symmetrical systems provide binocular vision.

The means by which scanning in elevation is accomplished, without introducing rotation of the field, is shown in Figures 10 and 11. The first mirrors of the right and left units are mounted at the ends of a single frame which rotates around the horizontal axis B (Figures 9 and 10), which passes through the center of the first of the three erecting mirrors, and allows the first mirrors at the ends of the frame to turn relative to the erecting systems. The three mirrors of the erecting system are rigidly connected to one another and turn at the same rate on a second horizontal axis, A in Figures 9 and 10, which passes through the centers of the third erecting mirror and of the first face of the prism. Rotation of the mirror-erecting system about the axis A is controlled by a belt

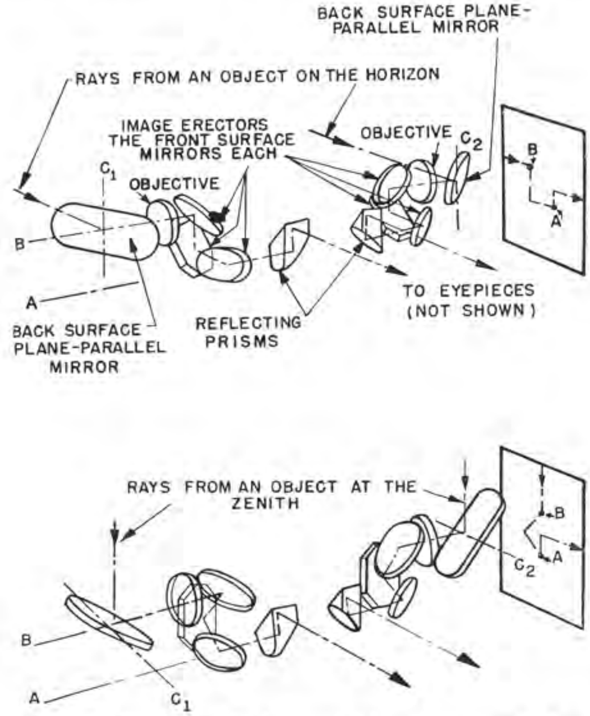

FIGURE 9. Optical layout of rolling cylinder scanner.

so that its rate is the same as that of rotation of the frame carrying the first mirrors around the axis B.

Scanning in azimuth is accomplished by rotating both first mirrors at the ends of the frames which carry them around the axes C_1 and C_2. They are linked together by means of

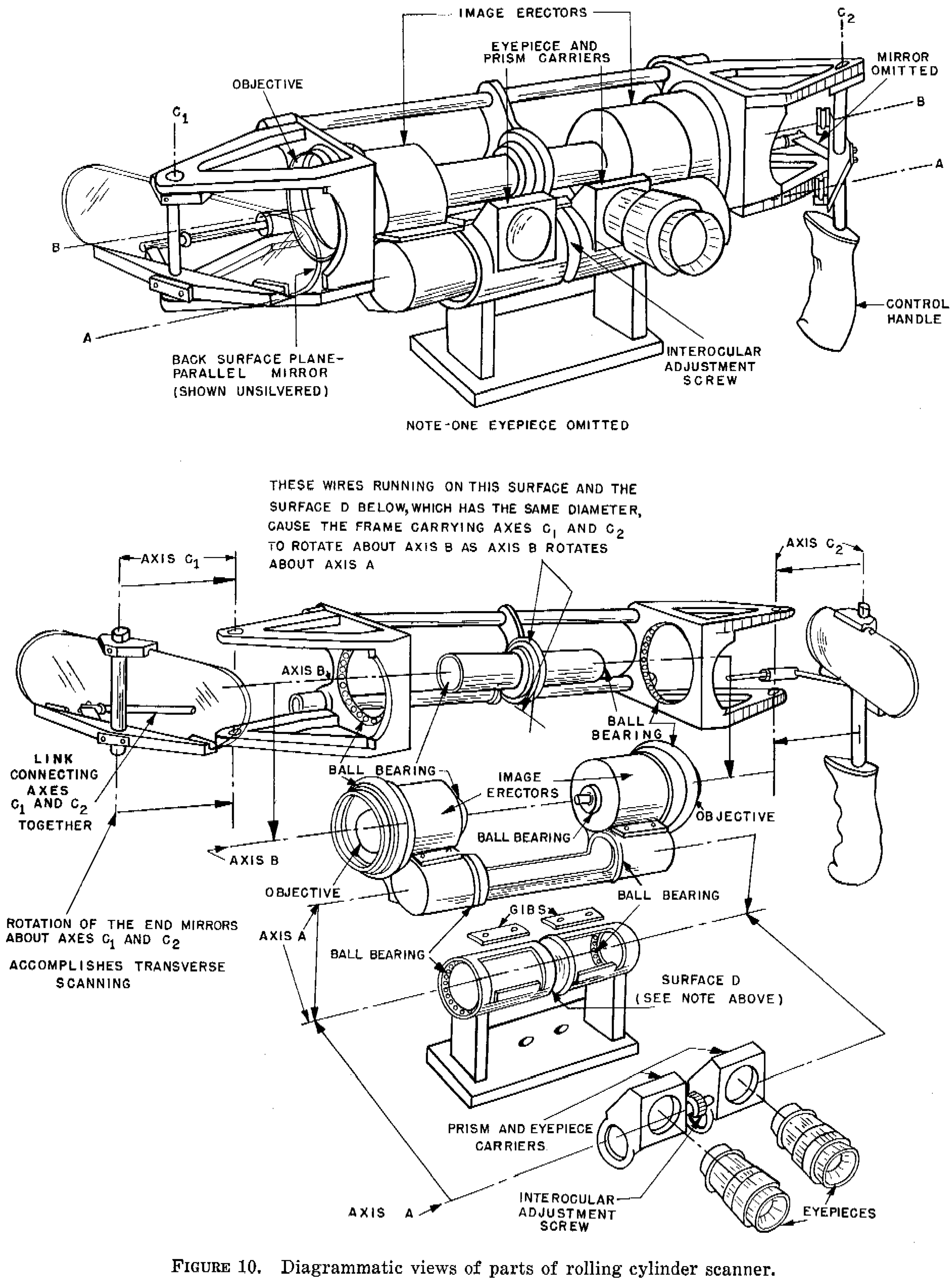

FIGURE 10. Diagrammatic views of parts of rolling cylinder scanner.

a bar which insures that they will always bear the correct relation to one another.

Careful adjustment of all six reflectors is necessary to insure that the two images will remain superposed when rotation is carried out about the axes *A*, *B*, and *C*. Such adjustment was actually achieved in the model built at Mount Wilson, but only by using special auxiliary mirrors previously oriented with the required accuracy.

Adjustment of interocular distance is provided by moving the prism which is attached to each eyepiece, along the axis *A*. A corresponding change in focal setting of the eyepiece is required.

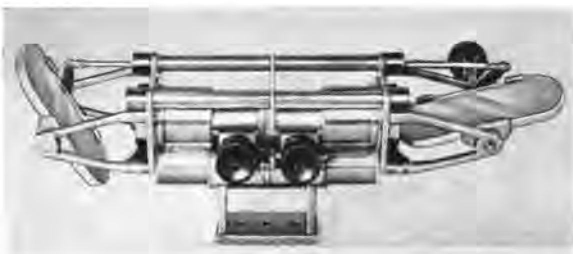

FIGURE 11. Rolling cylinder scanner.

A photograph of the complete device is shown in Figure 11. A pistol grip handle, shown in Figure 10, replaced the knob shown in Figure 11 after the photograph was made. Rotation of the handle on its own axis causes scanning in azimuth by rotating the end mirrors. The same handle is used to turn the two assemblies about the axes *A* and *B* to scan in elevation.

Marked simplification would result if this scanning device were made for monocular vision only.

Preliminary tests in searching for aircraft show that this device is entirely satisfactory from the observer's point of view. However, it should be noted that scanning is carried out around poles which lie in the horizon to the right and left of the observer, rather than around a pole at the zenith, as in the case of most of the other scanners described in this chapter. When the azimuth setting is not straight ahead, vertical scanning does not pass through the zenith but follows a minor circle centered at the poles in the horizon at the right and left. Thus it is not possible to add circles to the device which will show directly the elevation and azimuth of the center of the field.

16.4 DISCUSSION

A considerable variety of scanning devices have been designed and several models have been actually constructed. Time has not been sufficient to permit tests which are adequate for evaluating the usefulness of scanning devices in general in searching either for submarines or for aircraft. Indications are, however, that such devices may be distinctly useful, not only in searching for targets, but also in identifying enemy aircraft within or above a group of friendly aircraft, under conditions where radar is not effective.

Further tests will be necessary to determine which types of scanning devices are most satisfactory for various applications. It seems likely that for horizon scanning, where rotation of the image is definitely objectionable, the aircraft scanning chair, the panoramic scanner, or the altazimuth two-mirror scanner are likely to be most effective. For both horizon and sky scanning the aircraft scanning chair and the panoramic scanner have marked advantages on account of their inherent simplicity and general reliability.

16.5 RECOMMENDATIONS BY NDRC

1. In view of the great importance of the lookout problem, the study and development of scanning devices should be actively pursued.

2. Each of the promising types of scanning devices should be tested, with whatever improvements can be made in present models, on both submarine and aircraft targets. Every effort should be made to shield the observer from wind and cold and to increase his comfort. The score for detection should be compared directly with that obtained with hand-held binoculars. The subjective reactions of observers should be recorded in detail.

3. Experiments should be carried out to determine whether, when using a monocular, it is

[redacted]

advantageous to present the inactive eye with an illuminated field, and if so, what level of illumination is best.

4. A comparison should be made between monocular and binocular scanning devices of the same type, the monocular being provided with a comfortable headrest and eye guard, and with an illuminated field for the inactive eye if that has been found to be advantageous.

5. The most promising type of scanning device should be stabilized for use on shipboard, with the center of rotation near the eye of the observer. Experiments should be made to compare its effectiveness with that of hand-held binoculars.

6. The most successful scanning device should be provided with elevation and azimuth indicators in the field of view. Experiments should be carried out with selsyn linkage to remote indicators and to the fire-control system.

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Chapter 17

ANTIGLARE SHUTTER FOR NIGHT BINOCULARS

By *Sidney W. McCuskey*[a]

17.1 INTRODUCTION

OPTIMUM PERFORMANCE of the personnel making night observations in the operation of air or surface craft may be secured only if the eyes of the individuals concerned are dark adapted and remain so. The sensitivity of the eye to low light levels can be largely destroyed by even a short exposure to high brightness levels. When binoculars are used to increase the effective range of the eye the need for adequate protection against sudden flashes of illumination is even more acute.

The device to be described in the following pages[1] consists of a high-speed shutter to close the aperture of binoculars in a very small fraction of a second. Under Project AC-26 night binoculars with antioscillation mounts have been developed at the University of Rochester[2] and at the Eastman Kodak Company.[3,4] These units were designed for use by the pilot of a P-61 aircraft. Figure 1 shows the assembly mounted in the cockpit of this aircraft. The pilot can easily swing the binoculars into posi-

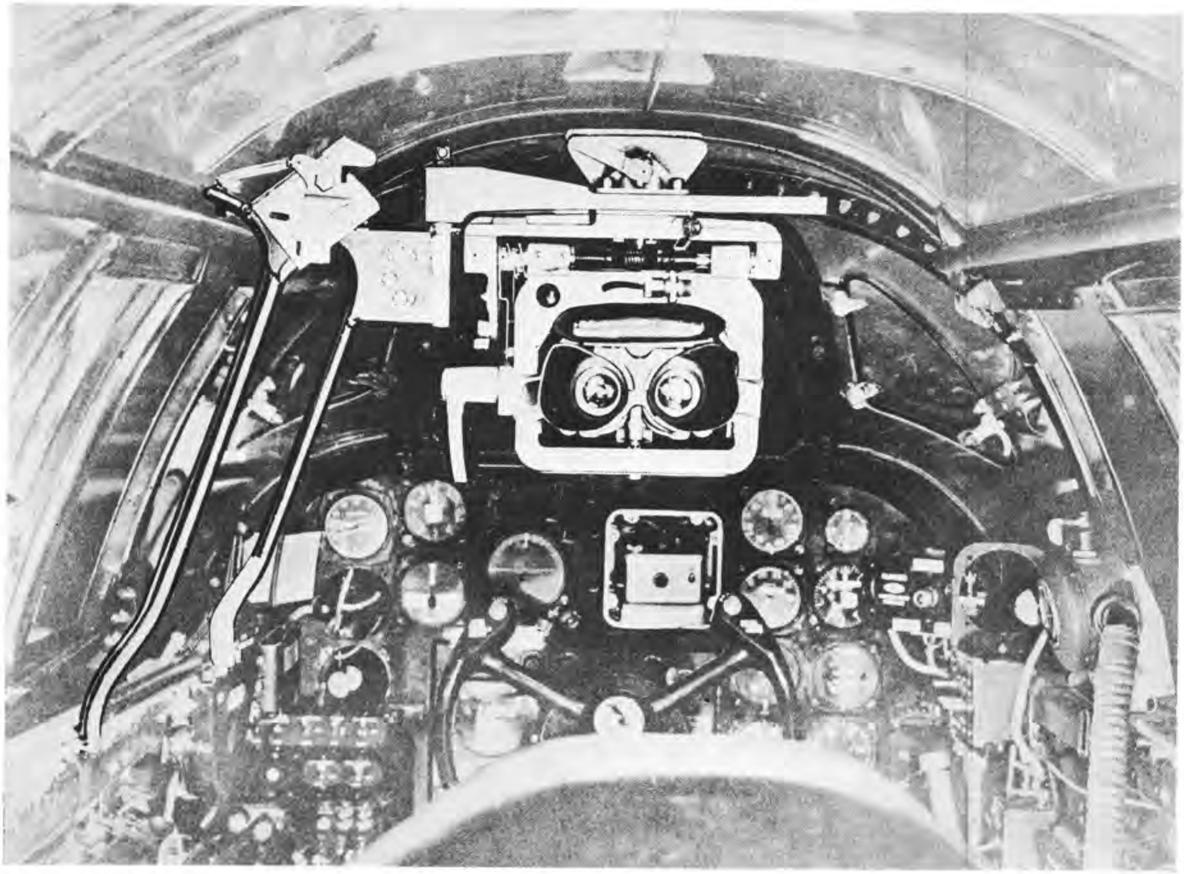

FIGURE 1. The antioscillation mount binoculars in the P-61 aircraft.

[a] Warner and Swasey Observatory of the Case School of Applied Science.

tion as he needs them. Protection for the pilot's eyes, should the enemy employ flares or flashes while the binoculars are in use, is afforded by the *antiglare shutter*. The shutter closes the aperture of the binoculars in about 0.0015 sec and remains closed for approximately 0.3 sec. A photoelectric trigger circuit to operate the device automatically has been developed at

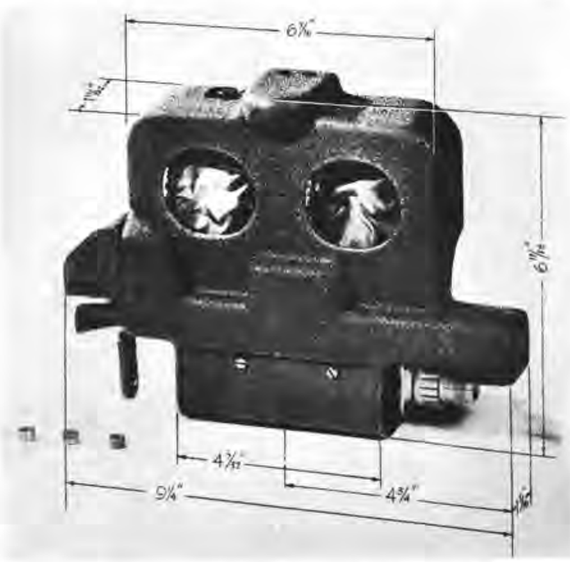

FIGURE 2. Front view of production model of the antiglare shutter.

Stanford University and is described in detail elsewhere.[5] Its essential features are given in the following pages.

17.2 THE HIGH-SPEED SHUTTER

Preliminary experiments with various methods of obtaining fast closure of the 2-in. diameter entrance window of the night binoculars indicated that electromagnetic or explosive propulsion of the shutter mechanism offered the greatest chances of success. It was desired to close this aperture in 0.001 to 0.0015 sec. Upon further investigation the electromagnetic propulsion was rejected. It was found impossible to drive a shutter the requisite 2 in. in less than 0.004 sec by this means. Further development, therefore, was centered on an explosively propelled shutter.

The framework and case of the shutter is an aluminum casting which may be rigidly connected to the aircraft night binocular. In the front surface of the casting are two apertures which are closed by the shutter curtains. Figure 2 gives a front view and Figure 3 a rear view of the device as a whole. All moving parts of the shutter are mounted on this casting.

It is evident that very high accelerations must be imparted to the shutter curtain by the explosive propellant. These are imparted to the curtains which close the apertures by means of a piston mechanism, within the "cylinder" shown in Figure 3. Experiment had indicated that the shock wave due to the explosion was insufficient to provide the required acceleration. Hence it was necessary to arrange the piston and cylinder so as to utilize as effectively as possible the expanding gases of combustion.

The cylinder, or barrel, which was finally adopted is a straight bored tube of mild steel rigidly fastened to the case. The piston moves freely inside the cylinder and has attached to it the shutter curtain yoke which passes from the piston to the blades through slots cut longitudinally in opposite sides of the barrel. The slots are made narrow to reduce as far as possible deceleration due to loss of gas pressure. This type of barrel has an added advantage in furnishing axial and rotational guides required by the piston and shutter blades during movement. A rubber bumper in the cylinder cap serves to dissipate the energy remaining in the piston at the end of its travel.

The piston itself is of carbon steel, hardened and drawn to 58 to 60 Rockwell C. It is essentially a cylinder whose central section has been reduced in diameter in order to conserve on weight. The ends have a bore diameter of 0.468 in., less the piston to bore clearance of 0.010 in. on the diameter, and serve as guide sections in the barrel. The lower section serves as the piston face.

Satisfactory materials for shutter curtains, capable of withstanding the high accelerations involved and being at the same time light and dependable in action, were found after considerable experimentation. Although a bellows-type curtain of cemented cloth and leather was found quite satisfactory, still better results

[redacted]

were obtained with a lightweight black nylon cloth, along both edges of which pure gum rubber cords were cemented. The cords are fastened so that in the relaxed state the curtain is pleated. These cords act as the return springs in withdrawing the curtains and also as supports for the nylon. The yoke, which carries the curtains, and the piston are shown in Figure 4.

will remain in either the locked or unlocked position. A linkage to the solenoid which indexes the propellant charges unlocks the catch after an appropriate time has elapsed.

Figure 4 gives a clear view of the magazine used to hold eight propellant units and Figure 3 shows it in position in the casting. The propellant units are recessed and held in place by a

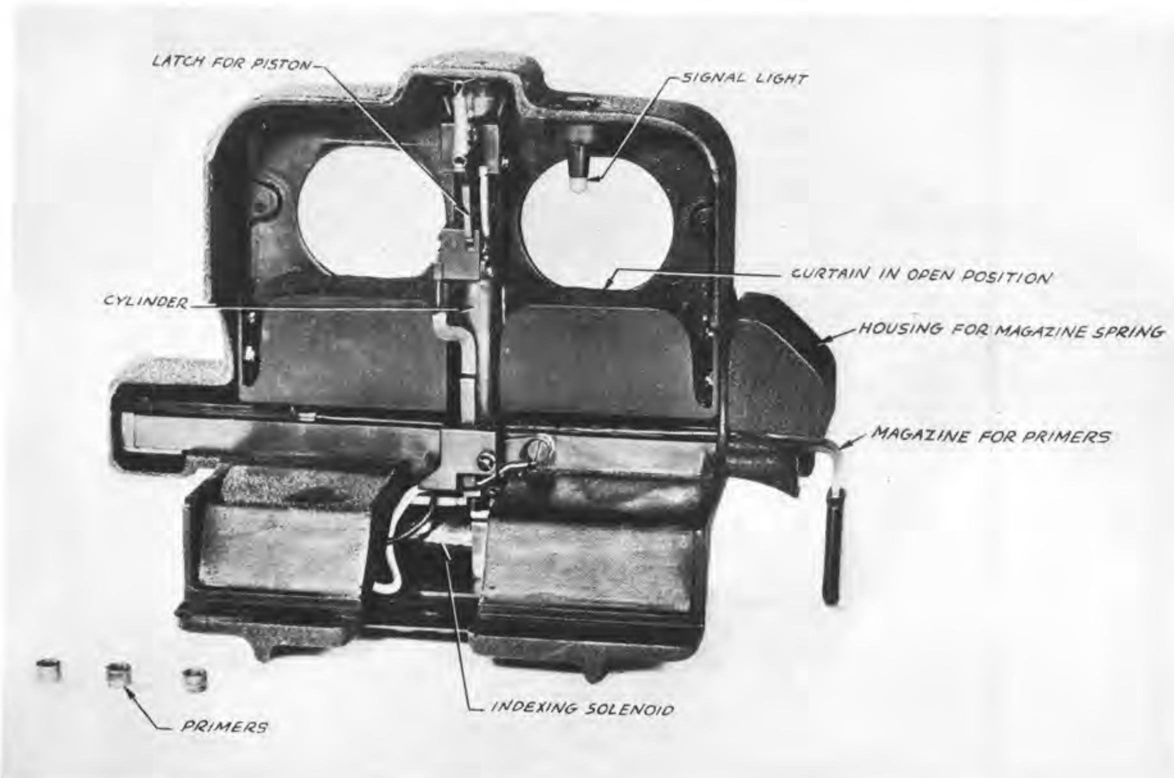

FIGURE 3. Rear view of antiglare shutter.

It is made of 0.040-in. steel, not beaded, and is of the uniform-stress cantilever design. Together with the piston it weighs 8.8 g.

In order that the shutter be held closed long enough for the observer's eye to be protected, a delay mechanism, retarding the reopening of the binocular apertures, has been provided. A catch, which will hold the piston in the "shutter closed" position (see Figure 3) for 0.3 sec, is the delaying mechanism. It is provided with a cam surface which is operated by the leading edge of the piston, while the locking portion of the catch is entered behind the trailing section. By a spring and detent mechanism the catch

hinged cover which does not interfere with the expanding products of combustion.

Attached to one side of the magazine is a ratchet whose pitch equals one-half the spacing between the charge units and whose alternate teeth lie on opposite sides of the ratchet bar. The magazine is placed in its chamber by pushing it against a spring until the last ratchet tooth engages the pawl and locks. Oscillating motion of the pawl allows the magazine to be moved by the spring. It is only necessary to trip the pawl and return it to its neutral position to bring a new propellant unit into place beneath the barrel. The pawl is actuated by a solenoid

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which operates on 24 v direct current and requires about 8 amp operating current. At the same time that the pawl is moved by the solenoid, the linkage to the delay catch holding the curtain closed releases the piston and allows the curtain to fall.

The delayed pulse needed to actuate the solenoid, thereby reopening the shutter and indexing the magazine, comes from the photoelectric circuit which initially tripped the shutter. It is described in Section 17.4. In case of electrical

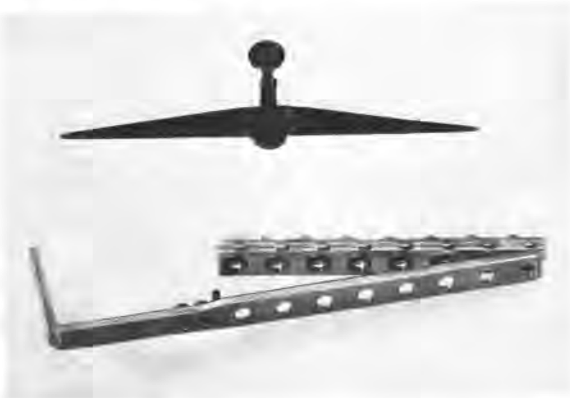

FIGURE 4. Piston and yoke assembly for the antiglare shutter are shown in the upper figure; the magazine is in the lower figure.

failure, a manually operated indexing lever mounted beneath the unit may be used to trip the indexing pawl and the delay catch lock.

A red signal light, mounted in such a way as to cast a dim diffuse glow, indicates when the magazine is empty.

17.3 THE EXPLOSIVE PROPELLANT

A low-voltage firing system (250 v) was found to be preferable to a high-voltage spark detonation system, both because of greater reliability in firing and because of the smaller amount of dielectric needed in the units. The propellant charge for this type of firing must be thoroughly mixed with a conducting material, the most suitable discovered being the carbon residue from the incomplete combustion of acetylene gas. A mixture producing about 0.25 megohm resistance gives satisfactory results at 250 v firing potential.

Many tests of priming materials were made in order to select a combination which would burn rapidly and leave no residue in the barrel after repeated firing. Tetrazene was finally selected. The end products of its combustion are various hydrocarbons and ammonia which condense to form a viscous tar. After a few firings the piston and barrel became gummed with this tarry residue. However, it was found that the residue could be solidified and be made in a sense self-removing by adding an oxidizing agent, potassium perchlorate.

The explosive charge which was found to work satisfactorily contained 65 per cent potassium perchlorate, and an additional 1.5 per cent acetylene black to act as a firing current conductor. A higher percentage of tetrazene results in a gummy residue; a lower percentage results in a sandy residue. The total charge weight found to be satisfactory for the purpose was 50 to 66 mg. This charge produced on the average a shutter closing time of 0.0013 sec. In the experimental stages the firing pulse was derived from a 0.5 μf condenser charged to 250 v.

A standard Remington Arms .60-caliber electric primer cup was used to case the firing unit. These cups are 0.220 in. long and have an outside diameter of 0.322 in. In the cups the cylindrical wall is electrically insulated from the bottom by a washer of acetate sheeting. The wall and bottom serve as the electrodes in the firing circuit. In order to increase the uniformity in explosion when such small charges were used the diameter of the primer bore was decreased to 0.187 in. A coating of nitrostarch lacquer protects the powder charge and decreases the chance that one unit will fire the adjacent one in the magazine.

17.4 THE PHOTOELECTRIC CONTROL CIRCUIT

The electronic circuit[5] which controls the action of the shutter performs the following functions:

1. It provides the impulse needed to fire the cap which closes the shutter curtain.

2. It actuates the relay which delays the reopening of the shutter curtain.

3. It operates the magazine indexing magnet which controls the flow of caps to the firing position.

Of the two hundred or more circuits and parts of circuits investigated, the one finally adopted is shown schematically in Figure 5. A brief description of its action is best followed by reference to the diagram.

When a light pulse of intensity 0.01 foot-candle (about that of the full moon directly observed) falls on the photoelectric cell T1 the voltage drop across R1 controls the grid of the coupling tube T2. The electric pulse is amplified by the succeeding stages of the amplifier and finally triggers a thyratron (T5) which becomes conducting and serves as a discharge path for the storage condenser C16. The current pulse thus released through the primary of the transformer (Tr) in turn creates a surge in the secondary which fires the cap, closing the shutter curtain.

The circuit required for reopening the shutter is connected to the firing circuit at the cathode of T5. When the cathode of the thyratron (T5) goes positive during the firing action, a positive pulse is sent to the grid of T6. This tube, which has been biased beyond cut-off, begins to conduct and energize Relay I, which in turn actuates the time-delay Relay II. Relay II operates the reopening release of the shutter. As explained in preceding paragraphs, the solenoid which releases the curtain catch also indexes the magazine containing the propellant caps. The completion of this cycle leaves the shutter ready for reclosing on a succeeding light flash.

While the preceding description gives the essentials of the circuit action, it does not make clear the particular features required for the present device. They will now be discussed.

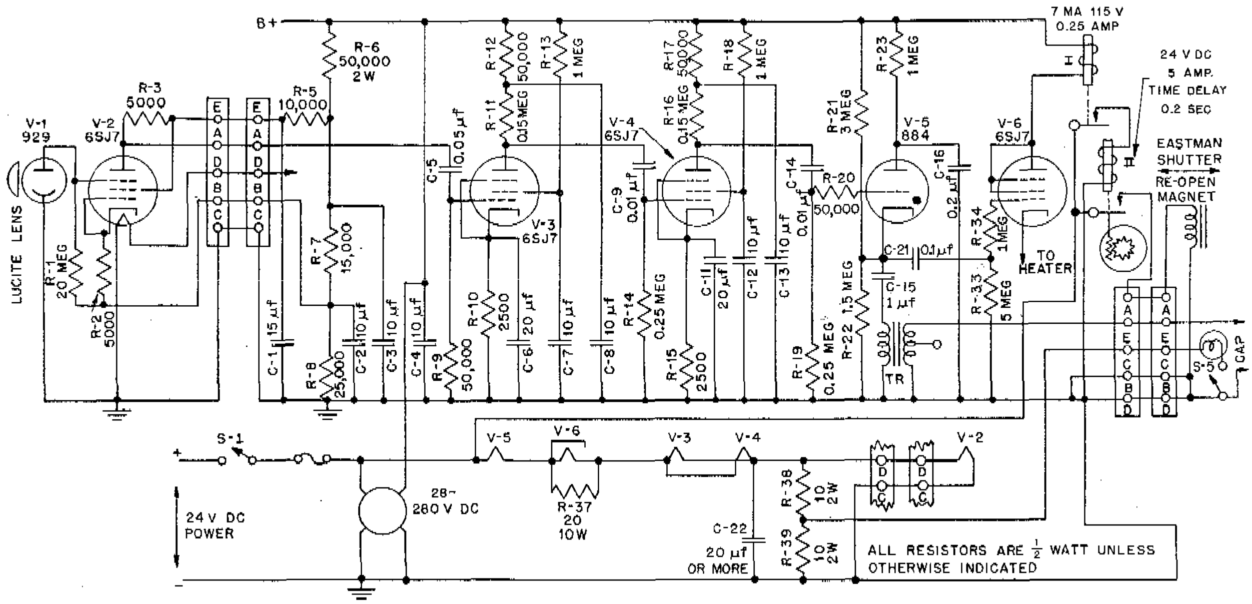

FIGURE 5. The circuit of the photoelectric control unit.

The Photocell Unit. The tube T1 is a 929 photocell, selected in this case because of its small size. It must be mounted in front of the pilot, and hence the entire unit was designed to restrict his view as little as possible. A cylindrical lens of Lucite placed before the photocell approximately doubles its light-gathering power. The photocell unit was designed to be mounted at the base of the gunsight. Considerable experimental work was required to determine a value for R1 which would provide sufficient sensitivity of the unit to light and at the same time not be too sensitive to the microphonics set up by vibration of the plane.

The circuit of the coupling tube T2 is somewhat unorthodox. Limitations of space pre-

[redacted]

cluded mounting the unit on springs to remove vibration due to motors, gunfire, and the like. To keep the voltage pulses due to physical vibration of the circuit elements at a minimum, therefore, they are mounted extremely solidly, leads are kept short and are of heavy wire, low electrode voltages are used, the suppressor grid of T2 is used as control, and everything is well by-passed to ground. An important feature of the circuit is the low impedances used. R3, for example, is only 5,000 ohms and it is this low value which prevents tube T3 from being sensitive to microphonics.

The tube T2 converts the signal in a resistance of 20 megohms to a signal of approximately the same voltage in a resistance of 5,000 ohms. There is little degeneration in the circuit because of the un-by-passed cathode resistor, as the current changes in the screen circuit act to compensate for changes in plate current.

An interesting feature of the circuit is the blocking action of T2 due to a large voltage developed across R1 when the light intensity incident on the photocell exceeds 1 footcandle. Irrespective of what the flare of light does after its initial burst, the entire circuit is blocked until the light intensity diminishes to 1 footcandle or less. No explosive caps will be wasted due to a flickering of the light source after the circuit has been triggered initially.

The Amplifier. The photocell unit connects to the main amplifier chassis by a 5-wire cable whose shield is grounded. In the amplifier, R5 and C1 form a decoupling filter in the plate supply of T2. This filter reduces the effects of transient surges in the power line due to current drain when the guns and cannon of the aircraft are fired or when the propellers are feathered.

T3 and T4 form a voltage amplifier in which the gain per stage is about 90 v. These stages are well decoupled to reduce the effects of transients.

The firing tube, T5, is an 884 thyratron which gives more reproducible firing characteristics than a strobotron. R21 and R22 form a voltage divider across the B supply to provide cathode bias for the 884. Even though the potential of the B supply changes due to current drain from the dynamotor supply voltage, the ratio of R21 to R22 is adequate to bias properly the thyratron.

When the grid of T5 is made more positive than the critical triggering value, capacitor C16 discharges through the thyratron. C16 thus shares its charge with C15, but since the latter has a very high capacitance relative to C16, most of the charge goes through the primary of transformer Tr, whose secondary connects to the explosive cap. C15 must be a paper condenser, for no leakage can be tolerated because of the necessarily high values of resistance in the voltage divider R21, R22.

Although the transformer is unnecessary for the firing of the cap, it does serve to isolate the cap so that one side of it may be at ground potential. Otherwise it would have been necessary to insulate the shutter from the frame of the plane. The characteristics of the transformer are not critical. The one used is a simple audio transformer.

A second reason for not connecting the cap directly in the discharge circuit of the thyratron is that, upon firing, the potential distribution on the capacitors might vary from cap to cap, since the latter show a variation in initial resistance of about 40 to 1, while the final resistance is virtually infinite. In such a case the operation of the reopening release circuit, which depends on the firing circuit, would be subject to erratic behavior.

When the cathode of T5 becomes positive and so makes T6 conducting, the Relay I is arranged to remain closed for 0.5 sec. This relay (operating at a current of 7 ma) energizes Relay II which takes 0.67 amp and which introduces a delay of 0.25 sec by means of an attached cylindrical disk of appreciable moment of inertia. About 0.5 sec after the cap is fired Relay I opens, Relay II opens, and the operation is complete.

The main chassis connects to the shutter by a 5-wire shielded cable. The large capacitor C22 helps to prevent surges on the 24-v power line from influencing the amplifier by induction through the long 10-ft cable that connects the main amplifier to the photocell unit. C22 should be as large as possible. Although 20 μf is used here, it is recommended that the size be increased, if space is available, up to 200 μf.

[redacted]

The bias for the thyratron cannot be obtained from tapping onto the heater leads as is done for T6 because, if that were done, the thyratron would fire when the unit is turned off, thereby wasting a cap. It is important to consider the *time constants* of the plate and cathode circuits together, for if they are not the same, or nearly so, the unit will fire a cap on either the make or break.

17.5 SUMMARY AND CONCLUSIONS

The antiglare shutter and its associated control circuit unfortunately were not completed until World War II was over. No flying tests of the device were made to determine its performance in an aircraft. In the laboratory, however, a few deleterious features of the production model became evident. They were principally mechanical sticking of the cross arm, which carries the curtains, at the top of its stroke, and breaking of the shutter stop cam repeatedly at a point where the cross section is small. These defects could easily be eliminated. In further design of such a device, simplification for servicing should be kept in mind. In its essentials the present shutter performs an adequate closure of the 2-in. binocular aperture in about 0.0015 sec.

If a new design of the antiglare shutter were to be made, it would be well to design the binocular as well as the shutter so as to place the latter at the smallest cross section of the light path. The aperture to be closed could then approach the dimension of the exit pupil. With this smaller distance of closure a mechanically operated shutter might prove adequate. Preliminary experiments carried out at Stanford University[5a] have already indicated that a mechanical shutter can be made to close the 2-in. aperture of the present device in 0.002 sec.

17.6 RECOMMENDATIONS BY NDRC

1. The shutter and photoelectric control circuit should be tested as a unit in flight, provided laboratory tests prove satisfactory. These tests should be planned to determine whether the sensitivity of the photoelectric pickup is adequate, whether microphonic effects have been adequately eliminated, whether the explosive drive is objectionable to the pilot, whether the closure of the shutter is fast enough to safeguard the dark adaptation of the pilot, and finally whether the mechanical performance of the shutter is dependable under service conditions.
2. Several minor mechanical changes should be made to improve the reliability of the shutter. These are described in the Stanford report.[5]
3. Experiments at Stanford indicate that it would probably be entirely feasible to make a mechanical shutter for a 2-in. aperture, which would be closed by release of steel springs in 0.002 sec. The photoelectric amplifier could probably supply about 15 ma at 200 v from a pentode to energize a laminated magnet which would hold the shutter open. When the pentode turns off the current, the magnet would let go the shutter with a very short delay.

Chapter 18

RAPID PROCESSING EQUIPMENT FOR PERISCOPE PHOTOGRAPHY

By *James G. Baker*[a]

18.1 INTRODUCTION

The Bureau of Ships requested that NDRC develop, under Project NS-242, an attachment for periscope cameras for submarines to give quickly developed film within a few seconds. It is frequently desirable to take a photograph while exposing the periscope above the surface of the water for the minimum possible time and then to study the photograph after the periscope has been withdrawn. This procedure can only be effective from a tactical point of view if the photographs can be examined within a minute of the instant of exposure and if the resolution is good.

Under Contract OEMsr-622 the Eastman Kodak Company was asked to investigate periscope photography and to provide rapid processing equipment for use at the periscope under conditions of warfare.[1] The project was initiated for the primary purpose of rapid processing, but led naturally to the subject of improving resolution.

18.2 RAPID PROCESSING EQUIPMENT

Tactically, it was desired to make photographs through the periscope of a submarine and to submerge for a short time for study of the situation under conditions of safety. Use of normal processing equipment meant lapse of time of many minutes which might alter the situation and render the photographs worthless.

The problem of securing a usable photograph approximately 1 min after exposure was brought to the attention of Eastman and solved in a short time. The standard camera used on periscopes was the Mark 1 35-mm periscope camera. It was thought desirable to adapt all equipment to this unit.

[a] Harvard College Observatory.

A special back was fitted to the 35-mm camera permitting the removal of short lengths of exposed 35-mm film for transfer without fogging to a processing tank. The light-tight processing cassette contains a knife for cutting the film to the correct length. The cassette is then immersed in the processing liquids which are able to pass through light locks to the film. Inside the cassette is a metal frame into which the film is automatically fed. This frame is removed from the cassette after processing and is placed in a special viewer under 3× magnification.

Camera Back

The Mark 1 periscope camera back was replaced exchangeably by a special back with slot at one end permitting the exposed end of the film to pass over into the special developing cassette. Film winding is accomplished by the normal frame counting recorder replaced by a winder. Guides are furnished to prevent curling of the film and misloading into the cassette. The cassette is provided with light traps with easy entry for liquids.

Cassette

The cassette is a small hard-rubber box, holding an internal metal frame into which the film is fed. An open side fitted with a light-locking cover permits assembling or removing the frame. The upper end of the cassette carries a knife and slotted anvil. With the knife retracted, film can pass over the anvil into the metal frame. Actuating the knife cuts the film and provides a light lock. Three frames are contained at once. The entire cassette is placed in the processing solutions.

A carrying case is provided with stainless steel tanks for the processing solutions. Spring-loaded covers prevent splashing of the chemicals from the tanks.

The processed negatives are viewed in a concave mirror-type viewer at threefold magnifi-

FIGURE 1

cation. The image may be viewed with both eyes from a relatively uncritical position.

Special film and special developer are used. Developing time is only 30 sec. The film is hardened beforehand to permit high processing temperatures, and to eliminate need for icing hot solutions. The complete periscope equipment consists of:

1. 1 Mark 1 periscope camera with special back
2. 3 Processing cassettes
3. 18 Film holders
4. 4 Processing tanks

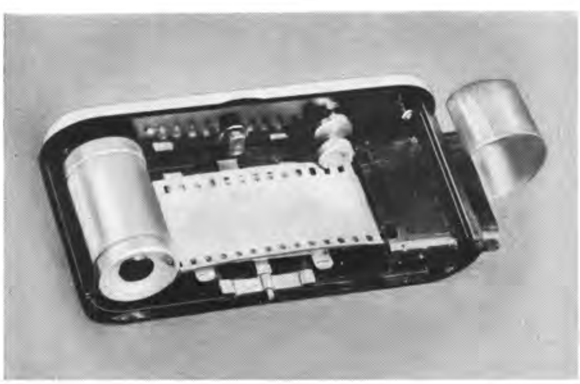

FIGURE 2

FIGURE 3

5. 1 Viewer
6. 2 Extra lamps for the viewer
7. 1 Extra starter for the lamps
8. 1 Carrying case

See Figures 1-9 for views of the rapid processing equipment.

18.3 PERISCOPE PHOTOGRAPHY

Following construction and test of the rapid processing equipment, a study was undertaken to find some means of improving the quality of submarine periscope photography.

A number of pictures were made aboard the

FIGURE 4

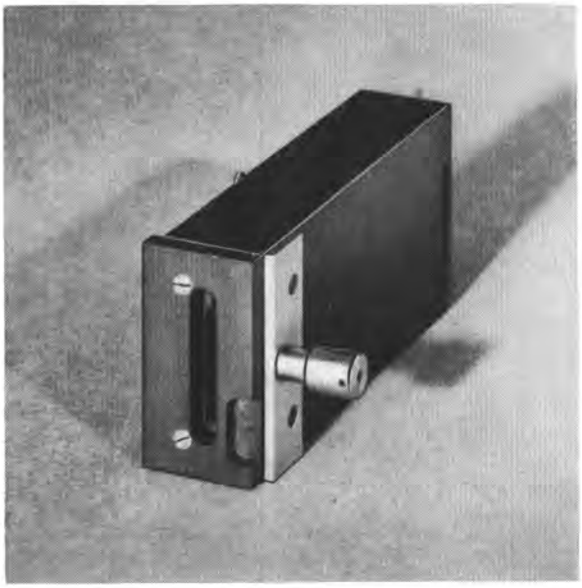

FIGURE 5

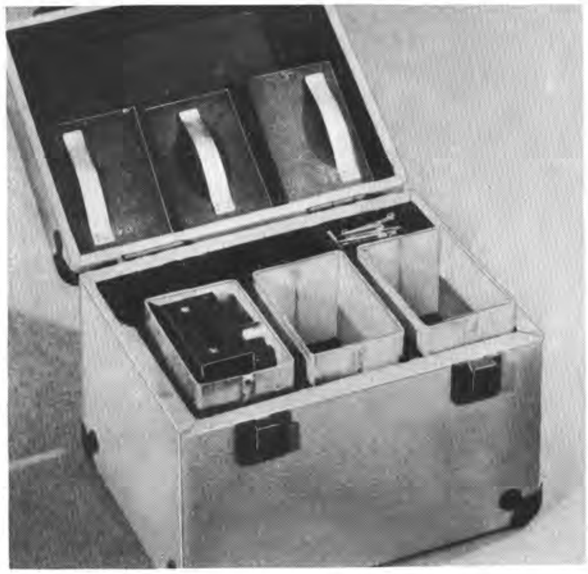

FIGURE 7

USS *Pilotfish,* but with poor results because of weather conditions. Another series of photographs were made through a Kollmorgen periscope, permanently mounted in the New Construction Training School at New London. A third series of photographs was made using a new Kollmorgen periscope with a 1.414-in. entrance window, mounted vertically in the Optical Shop and aimed across the Thames River.

FIGURE 6

In this latter work a resolution chart prepared by NDRC was used for quantitative judgment of the negatives. The following are the principal factors determining the quality of periscope photography.

1. Type of target.
2. Weather conditions.
3. Conditions at periscope entrance window.
4. The motion of the ship.
5. The optical system of the periscope.
6. The camera and taking lens.
7. The film and its treatment.

Of these seven points, the most important

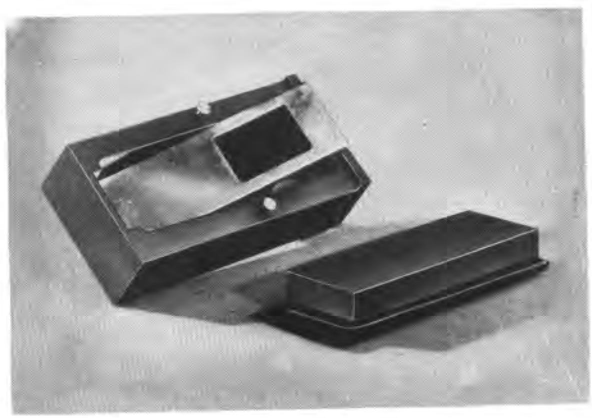

FIGURE 8

[redacted]

was found to be the optical system of the periscope. Observed resolutions in the first tests amounted to only 16 lines per mm, compared to the 45 or 50 lines per mm obtainable with a variety of fast films. Efforts were made to trace the contributions made by each factor, although all work was near the optical axis.

A study of the optical performance of the periscope indicated that its visual correction

FIGURE 9

for color aberrations was a predominating source of trouble photographically. The films used in the tests had been of B and C sensitizing and were specially sensitive to blue light. Moreover, the work was carried out near the surface of water, a notable scatterer of blue light. The curvature of field present in the periscope was also a source of trouble. Whereas the eye overcame the curvature by accommodation, the attached camera had to retain a flat image plane. It was considered that a special lens with overcorrected curvature might be used, but it was not felt to be a practicable solution.

A number of filter combinations were tried in special tests. Table 1 gives the chief results. From these tests the No. 12 Wratten filter seemed to give the best overall compromise. Thereafter, tests were made to determine the best exposure and the best camera lens to use with the periscope. The longer focal lengths gave longer exposures, because of the fixed exit pupil diameter. The following Ektar camera lenses were used.

50 mm	$f/12$
90 mm	$f/22$
153 mm	$f/38$

Thus, the 90-mm lens requires about four times and the 153-mm lens about nine times the exposure required for the 50-mm lens. On the basis of exposure time, which because of vibration and movement had to be shorter than

TABLE 1. Resolution measures with submarine periscope.

Filter	Exposure factor	Resolving power (lines per mm)	Best focal setting (ocular diopter)
C-5	5	16	1
61	7	23	0
16	3	19	0
4	1.5	16	
12	2	19	
16	3	19	
58	6	19	

$1/50$ sec, the longer focal lengths are undesirable and even unusable under average conditions. For general purposes it is believed that the 50-mm lens is the most satisfactory, at least until a more light-efficient periscope is available.

There is a definite advantage to be gained from the longer focal lengths in respect of definition. The following table shows the observed resolution.

50-mm No. 12	19 lines per mm	4 targets resolved
61	23 " " "	5 " "
90-mm No. 12	18 " " "	6 " "
61	18 " " "	6 " "
153-mm No. 12	20 " " "	7 " "
61	20 " " "	7 " "

At the time these exposures were made, visual observations were able to resolve only target 8, but with great difficulty. The nearly constant linear resolution should be noted.

ENTRANCE WINDOW CONDITION

Tests were made to determine the effect of the condition of the periscope entrance window. A 50-mm Ektar lens in an Ektar camera

[redacted]

was exposed on a resolution chart in the laboratory through a piece of grade B polished plate. Through a wet glass the resolution was variable, but generally very poor. Through the same piece of glass treated with an antiwetting agent, and then wetted, the resolution observed amounted to 50 lines per mm. A General Electric product called Dri-film was used and, indeed, seems a suitable treatment for periscope windows.

Visual Examination of the Periscope Color Characteristics

Visual tests were made by attaching an auxiliary 3× telescope to the periscope. The color curve of the auxiliary telescope was judged to be negligible in separate tests.

With the telescope ocular set at zero diopters, the periscope was focused without filters by examination of the line targets in the daytime and of a distant light source at night. All succeeding changes of focus were made by varying the ocular setting of the telescope.

Mean diopter settings of the telescope appear in Table 2.

Table 2. Visual measures of focus of periscope at several wavelengths.

	U.S. Periscope 92KA40T/1.4HA No. 1341			
	4,400 A	5,300 A	6,200 A	No filter
daylight	...	−0.25	−0.40	−0.21
	...	−0.14	−0.24	−0.19
night	−0.64	0.06	−0.07	...
	−0.54	0.07	−0.07	...

The report[1] states that when the exit pupil of the periscope was reduced to 2.2 mm and 1.6 mm by diaphragms, the image quality was improved markedly. It is concluded that the departure of the blue focus from the red and green foci undoubtedly contributes to the poor photographic results obtained with this periscope without filter.

18.4 RECOMMENDATIONS BY NDRC

1. Resolution tests should be made on distant targets, with the periscope mounted in an optical shop on shore, to determine the resolving power at various focal settings, using the standard camera and also cameras of several different focal lengths, with and without filters. The resolving power when photographs are taken through the periscope should be compared with the resolving power of the same camera and film, on the same targets, when the camera is used alone. The resolving power should be measured at various angular distances from the center of the field.

2. The glass-fluorite folded collimator (see Chapter 7) should be used for these tests with test targets at the focal plane if it can be made available. It was lost, at least temporarily, in the course of shipment from the Massachusetts Institute of Technology to the National Bureau of Standards. This collimator was made specifically for testing the photographic and visual performance of Navy periscopes.

3. The suggestions for improvements in periscope and camera design, which are outlined in Chapter 10, should be carried out.

4. Resolution tests should be made by photographing through a periscope with a submarine under way, under various conditions of roll and pitch, using resolution targets on a ship at a distance of about one-half mile.

5. The effect of wetting the periscope window with water should be determined by photographing through the instrument with the window wet and dry. If necessary, steps should be taken to remedy whatever loss of resolution is found to exist by using antiwetting agents.

[redacted]

Chapter 19

TWO-STAR NAVIGATING DEVICE

By *Theodore Dunham, Jr.*[a]

UNTIL THE DEVELOPMENT of Loran and other radio methods of navigation, the quick determination of longitude and latitude of an aircraft from observations of stars was of the utmost importance. Navigation tables and the Astrograph have greatly reduced the time and effort required to find the observer's position from observations of two stars. Nevertheless, an instrument which would display directly the position of the observer was much to be desired.

Previous attempts have been made to develop a two-star navigating device which will display position directly, but in all such instruments it has been necessary to hold the images of two stars simultaneously on a reticle mark. This has required guiding in three coordinates simultaneously, which is more than any observer can expect to do in an airplane which is always undergoing erratic excursions in roll, pitch, and yaw.

19.1 PRINCIPLE OF OPERATION

The Mount Wilson Observatory[1] developed a two-star navigating device which eliminates to a large degree the need for guiding in one coordinate. This was accomplished by providing one degree of freedom as a result of astigmatizing the two star images horizontally through the use of cylindrical lenses in front of each of the two telescope objectives.

A direct display of direction and distance to a selected target is achieved by bringing into the focal plane of the eyepiece of the instrument an image of a spherical bubble as well as the two star images. The instrument is set in advance of take-off so that, if it were at the target, the two star images would coincide on the reticle mark, with the bubble also on the reticle mark. A clock drive maintains the setting for the target by counteracting the apparent motion of the stars. For any location of the aircraft other than over the target, the direction and distance of the bubble from the center of the reticle indicates the course and distance to the target, provided the two stars are held coincident on the center of the reticle.

19.2 DESIGN AND CONSTRUCTION

Figures 1 and 2 show a photograph of the complete instrument and a diagrammatic view of the optical and mechanical parts. The axis on which the instrument is turned by clockwork is set parallel to the earth's axis. Light from the two stars is combined and carried down the axis to an objective, right-angle prism, and eyepiece. Light from star A enters the instrument through an astigmatizing cylindrical lens and is directed down the polar axis by a pentareflector which is designed to produce a deviation equal to 90 degrees plus the declination of the star. Light from star B also enters through an astigmatizing cylindrical lens and is directed down the polar axis by a pentareflector designed for its declination. The pentareflector for star B has a hole cut in it which allows a beam from star A to pass through it which has a diameter equal to half the aperture of the objective. Thus the beams from the two stars are combined and focused by the objective on the reticle. Pentareflectors are used to avoid the need for precise setting of the reflector units. The pentareflectors are set on the polar axis with an included angle between them equal to the difference of the right ascension of the two stars. A separate pentareflector is made for each star. In a final model, each pentareflector would be located with dowel pins.

A Dove prism has been included in the prototype model, to rotate the astigmatized image of star A for an alternative method of using the instrument, but this is not needed.

A clock rotates the entire unit about the polar axis once in 24 hours through a system of steel belts.

[a] Chief, Section 16.1, NDRC.

[redacted]

The level bubble is illuminated at the focus of a telephoto system which sends a parallel beam into the instrument through the transverse axis by means of two right-angle prisms. The bubble and optical system are mounted as a unit and rotate about the transverse axis. The polar axis is rotated about this transverse axis until it makes an angle relative to the plane defined by the bubble which is equal to the latitude of the target. A vernier sector permits setting to 1 min of arc. A fine screw attached to this sector provides leveling (guiding) about the E-W axis. A fine screw attached to the base provides leveling (guiding) about the N-S axis. The entire instrument rotates in a ring within the base for setting in azimuth.

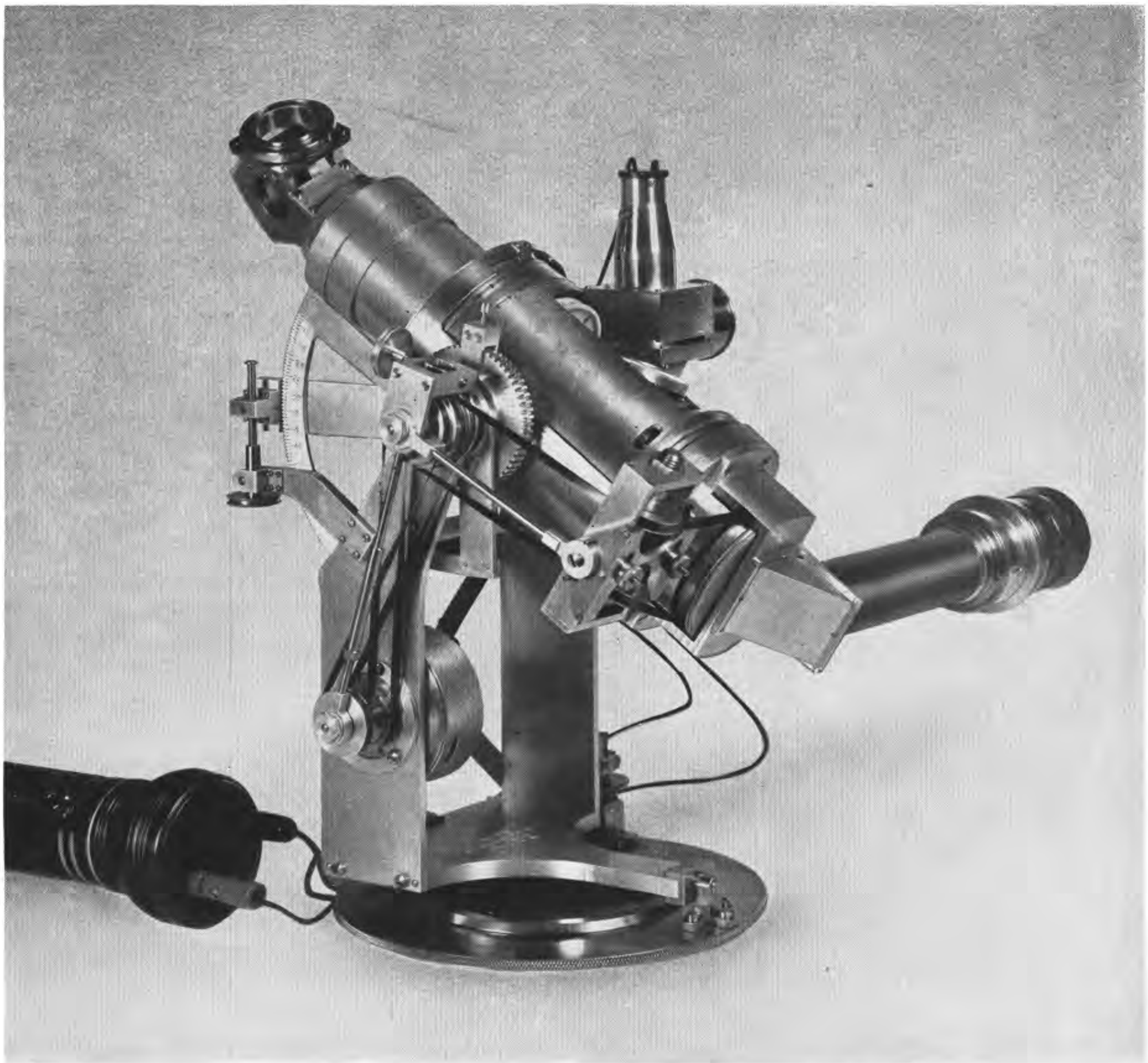

FIGURE 1. Photograph of two-star navigating instrument.

The cylindrical lenses are set with their axes nearly horizontal, with the aid of a fiducial mark which is set opposite a small steel ball which always rolls to the bottom of a circular track. The two star images are, therefore, astigmatized horizontally, with the result that the point of intersection of the two lines, into which the point images are converted, is extremely insensitive to the setting of the instrument in azimuth. It is this feature of the instrument

which makes it likely that it can be operated satisfactorily by an observer, since he would be required to maintain the setting of the instrument in only two coordinates by guiding with the leveling screws.

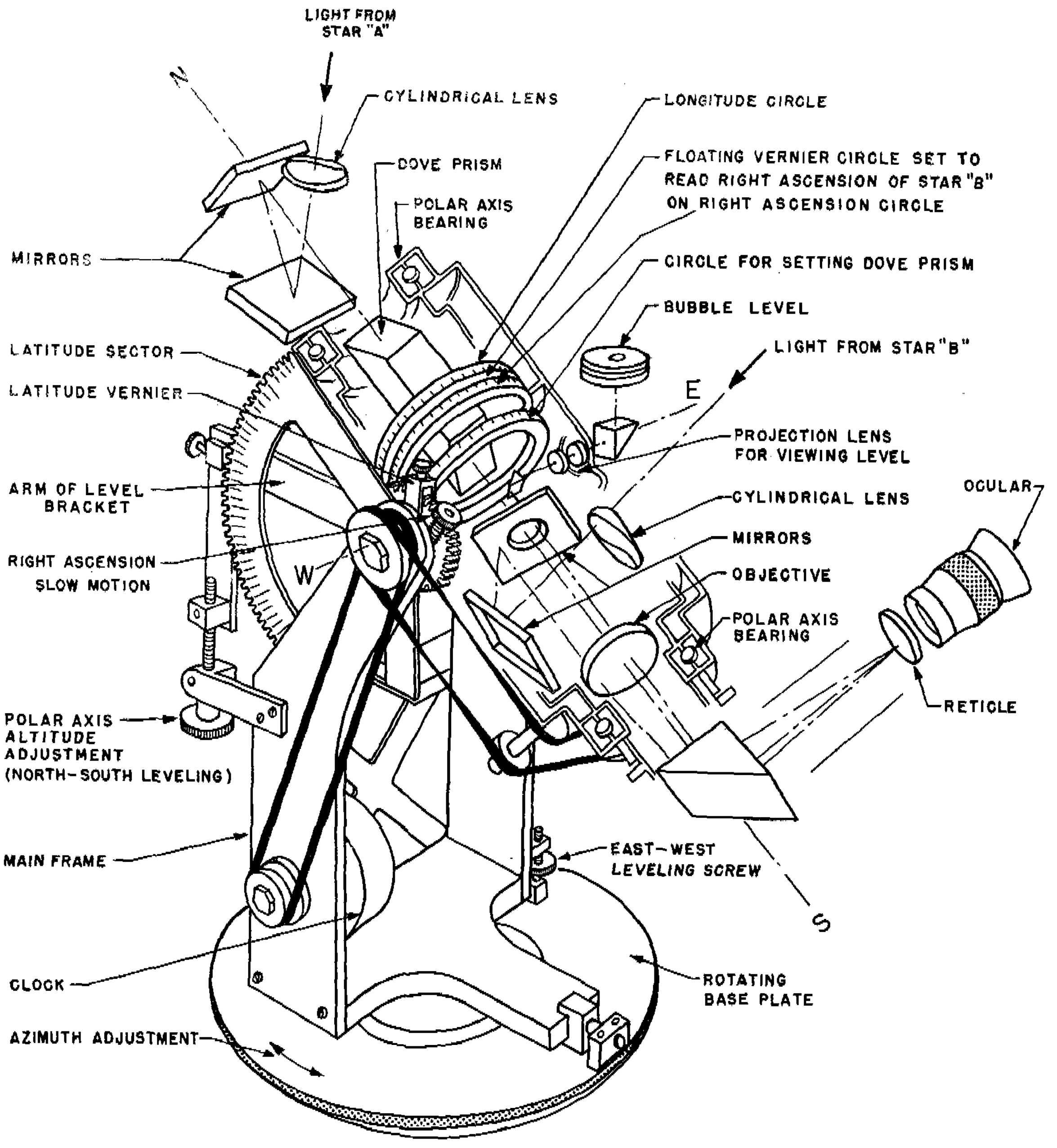

FIGURE 2. Arrangement of optical and mechanical parts.

Figure 3 shows the display in the field. The intersection of the two star line images is held at the center of the reticle (method A). The course and distance to the target are observed by noting the position angle of the bubble and its distance from the center of the reticle. Obviously, the reticle could be replaced by a transparent map, illuminated with faint red light, on which the bubble would indicate directly the position of the aircraft.

The same instrument may be used in a different way, namely, guiding in level to hold the spherical bubble at the center of the reticle and

noting the location on the reticle of the intersection of the star image lines (Figure 3, method B). In either case some averaging will be required because linear accelerations of the aircraft will displace the bubble. For this reason its period should be as long as is consistent with free motion.

The most attractive method for operation

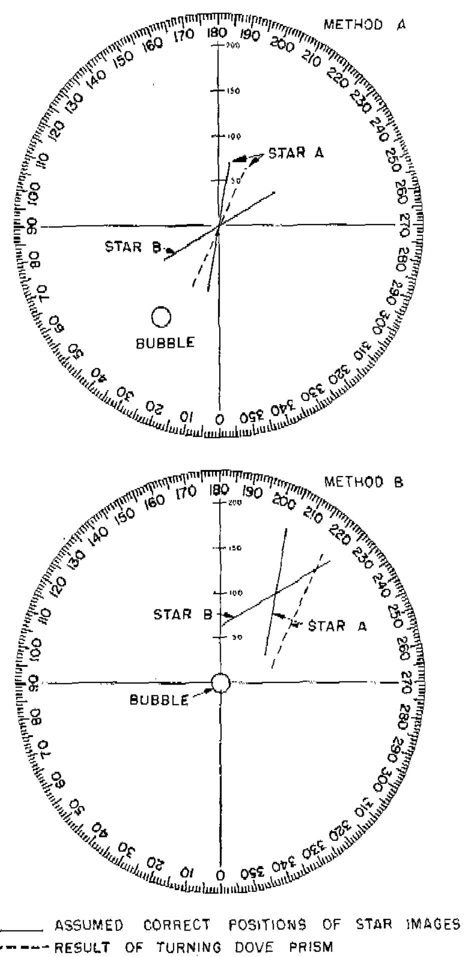

FIGURE 3. Display of reticle, star image lines, and bubble.

would obviously be to stabilize the base of the instrument so that it would be held always level. The bubble could be dispensed with if this were done, and it would then merely be necessary to observe the position where the star lines intersect on the reticle. This would involve much more mechanism, however, and would eliminate the advantage of fundamental simplicity and independence of other equipment which the present instrument possesses.

19.3 TESTS

Qualitative tests show that stars of moderate brightness can be picked up and that the astigmatized image lines are bright enough for easy setting on the reticle. When the images are astigmatized horizontally, the desired result is achieved, namely, the intersection of the two images is not displaced on the reticle when the instrument is rotated through small angles in azimuth. The observer soon learns how to set this intersection at the center of the reticle by manipulating the adjusting screws, although the direction in which motion is required is often quite unexpected.

It was not possible to conduct tests in an airplane, but it seems clear that the device would operate as expected.

The prototype model has been transferred to the Bureau of Aeronautics.

19.4 CONCLUSIONS

The present model demonstrates the feasibility of constructing a two-star navigating instrument with astigmatized images. The parts of any future model should be made stronger to reduce flexure. The design could probably be considerably simplified by eliminating some of the adjustments on individual optical units which are included in the present instrument.

For the quickest and most convenient operation, the instrument should be stabilized so as to hold its base level within the desired accuracy for navigation. The observer would then be required to guide only very approximately in azimuth and to note his position by merely noting where the two star image lines intersect on a transparent map illuminated with red light. Some averaging would be required due to linear accelerations of the aircraft, but probably less than when a relatively short period bubble must be averaged.

19.5 RECOMMENDATIONS BY NDRC

1. The design of the navigating instrument should be simplified and greater rigidity should be provided.

2. Tests of the present instrument should be made in an airplane, using the method in which the star image lines are held on the reticle while the position of the spherical bubble is read to give the position of the aircraft.

3. The instrument should also be tested on a stabilized platform, so that the observer can read his position directly from the position of the intersection of the star lines on the reticle, without the use of a bubble.

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APPENDIX

I. Chapter 1

TABLE 1. List of lenses tested at Wright Field.

Focal Length	Relative Aperture	Manufacturer	Lens Name	Remarks
3 in.	$f/6.3$	Bausch and Lomb	Metrogon	For T-7 camera. Not standard.
4 in.	$f/2.8$	Harvard College Obs.	Spherical Wide-Angle	120° Wide-angle. Experimental.
5.6 in.	$f/2.5$	Harvard College Obs.		Ophthalmic glass lens. Small scale prototype of 7-in. $f/2.5$ for K-24 camera. Experimental.
6 in.	$f/2.8$	Eastman	Aero-Ektar	For K-24 camera. Experimental.
6 in.	$f/6.3$	Bausch and Lomb	Metrogon	For K-17, K-22, T-5, S-7. Standard.
6⅜ in.	$f/4.5$	Wollensak		For K-24, K-20, K-25 cameras. Experimental.
6⅜ in.	$f/4.5$	Eastman	Anastigmat	For K-20, K-24, and K-25 cameras. Standard.
6⅜ in.	$f/4.5$	Bausch and Lomb		For K-20, K-24, and K-25 cameras. Experimental.
6.7 in.	$f/2.6$	Harvard College Obs.		Ophthalmic glass lens. For K-21, K-24 cameras. Experimental.
7 in.	$f/2.3$	Harvard College Obs.		Ophthalmic glass lens. For K-21, K-24 cameras. Experimental.
7 in.	$f/2.5$	Harvard College Obs.		For K-21, K-24 cameras. Experimental.
7 in.	$f/2.5$	Polaroid		Plastic lens for K-21, K-24 cameras. Experimental.
7 in.	$f/2.5$	Eastman	Aero-Ektar Aerostigmat	For K-21 and K-24 cameras. Standard.
7.1 in.	$f/2.8$	Curtis		Plastic lens for K-21 and K-24 cameras. Experimental.
7.6 in.	$f/4.5$	Bausch and Lomb		For K-21 and K-24 cameras. Experimental.
8 in.	$f/1.5$	Eastman	Aerostigmat	For K-24 camera. Experimental.
8 in.	$f/2.7$	Bausch and Lomb	Anastigmat	For K-21, K-24 cameras. Experimental.
8 in.	$f/2.8$	Bausch and Lomb	Anastigmat	For K-21, K-24 cameras. Experimental.
8 in.	$f/3.2$	Curtis		Plastic lens for K-21, K-24 cameras. Experimental.
12 in.	$f/2.5$	Eastman	Aero-Ektar	For K-19 camera. Standard.
12 in.	$f/2.5$	Bausch and Lomb	Anastigmat	For K-19 camera. Experimental.
12 in.	$f/4$	Bausch and Lomb		For K-22 camera. Experimental.
12 in.	$f/4.3$	Curtis		Plastic lens. Experimental.
12 in.	$f/5$	Eastman	Aerostigmat Anastigmat	For K-17, K-22 and K-24 cameras. Standard.
12 in.	$f/6.3$	Bausch and Lomb	Metrogon	For K-27 camera. Standard.
13½ in.	$f/3.5$	Eastman	Aero-Ektar	For K-19 camera. Not standard.
15 in.	$f/5.6$	Eastman	Telephoto	For K-21, K-24 cameras. Experimental.
20 in.	$f/5.6$	Bausch and Lomb	Telephoto Anastigmat	For K-24 camera. Standard.
24 in.	$f/5.6$	Eastman	Telephoto	For K-24 camera. Experimental.
24 in.	$f/6$	Bell and Howell	Acrotar	For K-17, K-22 cameras. Experimental.
24 in.	$f/6$	General Scientific	Aero-Scienar	For K-17, K-22 cameras. Experimental.
24 in.	$f/6$	Perfex Corp.		For K-17, K-22 cameras. Experimental.
24 in.	$f/6$	Bausch and Lomb	Aero Tessar	For K-17, K-18, K-22 cameras. Standard.
24 in.	$f/6$	Eastman	Aero-Ektar	For K-17, K-18, K-22 cameras. Standard.
36 in.	$f/8$	Harvard College Obs.	Fluorite	For K-22 camera. Experimental.
36 in.	$f/8$	Harvard College Obs.	Telephoto	For K-17, K-18, K-22 cameras. Experimental.
36 in.	$f/8$	Eastman	Telephoto	For K-17, K-18, K-22 cameras. Experimental.
40 in.	$f/5$	Harvard College Obs.	Telephoto	For K-22 camera. Standard. Pressure compensated and temperature controlled.
40 in.	$f/5.6$	Eastman	Telephoto	For K-22 camera. Experimental.
40 in.	$f/5.6$	Bausch and Lomb		For K-22 camera. Standard.
40 in.	$f/8$	Bausch and Lomb	Telestigmat	For K-15, K-17, K-22 cameras. Standard.
48 in.	$f/6.3$	Bausch and Lomb	Telephoto	For K-22, K-32 cameras. Experimental.
48 in.	$f/6.3$	Eastman	Telephoto	For K-22, K-32 cameras. Standard.
60 in.	$f/6$	Harvard College Obs.		For K-22 camera. Experimental.

TABLE 2. List of lenses tested at R.A.E.

Focal length	f/No.	Name	Remarks
0.5 in.	f/3.5*	Dallmeyer Reversed Telephoto	Instrument recording and cine work. British Patent 572086.
0.54 in.	f/6	Dallmeyer Anastigmat	Recording of instruments.
1 in.	f/2.5	Wray Lustrar	" " "
1 in.	f/2.5	Ross	" " "
1 in.	f/2.5	Dallmeyer	" " "
1 in.	f/2.8	Taylor, Taylor, and Hobson	" " "
1 in.	f/3.5†	Ross	" " "
1 in.	f/3.5†	Dallmeyer	" " "
1 in.	f/3.5†	Wray	" " "
1½ in.	f/1.9	TTH	C. R. T. recording.
35 mm	f/3.5	Wray	Instrumentation.
2 in.	f/1*	Wray	C. R. T. recording.
2 in.	f/3.5†	Dallmeyer	For G.45 camera gun (Ph. 303, 246, and 228).
2 in.	f/3.5†	Kodak	" " " " " " " " "
2 in.	f/3.5†	N.O.C.	" " " " " " " " "
3 in.	f/3.5	Wray	Instrument and C. R. T. recording.
3 in. (75 mm)	f/3.5	Ross Tessar	Instrument recording.
3¼ in.	f/5.5*	Ross W. A. Survey	Air Survey lens (5"x5") 190/H1237.
3.7 in. (93 mm)	f/4.5	Ensign Ensar	For enlarger type D.
4 in.	f/4.5	Dallmeyer	For enlarger type D.
4 in.	f/1.5	Kodak (J. L. Houghton)	Experimental for night work 190/H1237.
5 in.	f/2.9	Dallmeyer Pentac	Hand-held and twin-mirror cameras.
5 in.	f/4†	Ross W. A. Xpres	For F.24 camera.
5 in.	f/5.6	Ross W. A. Xpres E.M.I.	Experimental for F.24. Not adopted (Ph. 137).
5 in.	f/5.5	Ross W. A. Xpres E.M.I.	Experimental for F.24. Not adopted (Ph. 137).
5 in.	f/4.5	Ross W. A. Xpres	Experimental for F.46. Not adopted (Ph. 250).
5 in.	f/4.5†	Wray	For F.46 camera (Ph. 250).
5 in.	f/4†	Ross	Special design for F.46 camera.
5 in.	f/3.5	TTH Series IIa	Experimental for hand-held camera. Not accepted.
5¼ in.	f/2.5	TTH Series X	" " " " " "
5½ in.	f/6.3	Thompson-Courtauld	Experimental for F.24. Not accepted. (Ph. 125).
5½ in.	f/6.3	Dallmeyer	Process lens.
6 in.	f/2	TTH (5 component)	Experimental lenses for night photography. Not adopted (PRC.37/44).
6 in.	f/2	TTH (4 component)	Experimental lenses for night photography. Not adopted (PRC.37/44).
6 in.	f/5.5	Ross W. A. Survey	Air Survey lens for 9x9 in. (various NPL reports).
7 in.	f/4	Ross Xpres	For 7x7 in.
8 in.	f/1.5	Kodak	For night photography (114/H1055 and Ph.341).
8 in.	f/5.6†	TTH Aviar	For 5x5 in. (F.24) (38/H881).
8 in.	f/1.9	Dallmeyer	Experimental for night use. Not adopted.
8 in.	f/2.9	Dallmeyer Pentac	F.24 camera (day and night) 2/H697 and A2/H882.
8 in.	f/4	Dallmeyer Pentac	Experimental. Produced in small quantities.
8 in.	f/2.9	Dallmeyer Pentac	With rare-earth glass components (Ph.257).
8¼ in.	f/4	Ross Xpres	For 7x7-in. air camera and process work.
9 in.	f/2.5	TTH	Experimental for night use. Not adopted (PRC.37/44).
9½ in.	f/6.3	Wray Lustrar	Experimental for F.24. Not adopted.
10 in.	f/4	Ross Xpres	For 7x7-in. (F.8) camera and process work.
10 in.	f/8	Aldis Anastigmat	Process work.
10 in.	f/6.3	Ross W. A. Xpres	Experimental. Not adopted (Ph. 127). (For 7x7 in.)
10 in.	f/1.6	TTH	Experimental for night photography. Not adopted.
10½ in.	f/6	TTH Aviar	Experimental for F.24 and F.8. Not accepted (Ph.136).
12 in.	f/7.7	Dallmeyer Dallon	For ground use (telephoto).
12½ in.	f/1.5	TTH	Experimental for night use. Not adopted.
12½ in.	f/2	TTH	Experimental for night use. Not adopted.
14 in.	f/1.8	TTH	Experimental for night use. Not adopted.
14 in.	f/4.5†	Dallmeyer Serrac	For F.24 camera.
14 in.	f/5.6	Dallmeyer Serrac	For F.24 (experimental). Produced in small numbers.
14 in.	f/5.6†	Dallmeyer Anastigmat	For F.8 (7x7 in.).
14 in.	f/5.6†	TTH Aviar	For 9x9 in. and F.52. 38/H881.
20 in.	f/5.6	Aldis Triplet	39/H.884 (for 9x9 in., but used on 5x5 in.).

TABLE 2. (*Continued*)

Focal length	f/No.	Name	Remarks
20 in.	f/6.3	Dallmeyer Anastigmat	For 9x9 in. Experimental, not adopted (109/H1039 and Ph. 134).
20 in.	f/6.3†	Ross Survey E.M.I.	Standard lens for F.52 (109/H.1039 and Ph. 135 and others).
20 in.	f/6.3	Cooke Aviar	Experimental for 9x9 in. Not adopted (Ph.133).
20 in.	f/6.3	Ross Survey E.M.I.	Redesigned (Calc. III) (Ph.308).
20 in.	f/5.6†	Cooke Telephoto	For F.24 camera. Standard telephoto.
20 in.	f/5.6†	Dallmeyer Dallon	For F.24 camera. Standard telephoto.
20 in.	f/6.3†	Ross Telephoto	For F.24 camera. Standard telephoto.
20 in.	f/6.3*	Ross Xpres	Successive prototype for F.52 (161/H.1261, Ph.252, Ph.296, Ph.288).
20 in.	f/6.3	Ross Astro Aero	Prototype for F.52 (Ph.261).
20 in.	f/6.3	Kodak Triplet	Prototype for F.24. Not adopted (35/H.885).
20 in.	f/5.6†	TTH Aviar (1918)	Standard for F.52 camera (26/H.852, 44/H906 112/H.1061, and Ph.305).
20 in.	f/5.6†	TTH Aviar	Production model in early part of World War II (Ph.305).
20 in.	f/5.6†	TTH Aviar	Redesigned production type (later in World War II) Ph.305.
20 in.	f/8	TTH Design 287:903:11	Prototype for F.52 (Ph. 258). Not adopted.
20 in.	f/8	TTH Design 327:112	Experimental for F.52. Not adopted (Ph.297).
20 in.	f/8	TTH Design 327:323	Experimental for F.52. Not adopted (Ph.297).
20 in.	f/9.5	TTH No. 284084	Experimental for F.52. Not adopted (Ph.297).
20 in.	f/5.6	Ross Aero	World War I lens, used in F.24 camera.
20 in.	f/4.5	TTH Aviar	1918 lens for 9x9 in.
25 in.	f/6.3*	Ross Xpres	Twelve produced (Ph.335 and Ph.343).
30 in.	f/6.3	Ross Astro Aero	Experimental for F.52. Some produced (Ph.166, 98/A1012).
36 in.	f/6.3†	Booth Telephoto (Dallmeyer)	Standard for F.52 (Ph.289 and Ph.317).
36 in.	f/6.3†	Booth Telephoto (TTH)	Standard for F.52 (Ph.289 and Ph.260).
36 in.	f/6.3†	Booth Telephoto (Ross)	Standard for F.52 (Ph.289 and Ph.325).
36 in.	f/6.3†	Booth Telephoto (Canadian)	Standard for F.52 (Ph.318).
36 in.	f/6.3	Ceilar Telephoto (Australian)	Similar to Booth Telephoto. Prototype (Ph.318).
36 in.	f/6.3*	Wray Telephoto	Prototype. Development of Booth (Ph.328).
36 in.	f/6.3	Ross Telephoto	Experimental for F.52 (Ph.342).
36 in.	f/6.3	Booth Telephoto (figured)	Various lenses figured by Hilger or Burch (Ph.260, Ph.326).
40 in.	f/8	Dallmeyer Dallon	Used in F.52 before production of Booth Telephoto.
50 in.	f/8*	Ross Telephoto	Experimental for F.52 (Ph.316 and Ph.343).
56 in.	f/8	Ross Telephoto	Prototype for F.52. Not accepted (Ph.263).
56 in.	f/8	Cooke Telephoto	Commercial type tested for F.52 but not adopted.
32 cm	f/3.5	Xenar	German lens tested in U.K. (Ph.334).
7 in.	f/2.5	Kodak Ektar	Tested for F.24 camera (Ph.306).
20 cm	f/6.3	Zeiss Topogon	German W.A. Survey lens (Ph.299).
75 cm	f/6.3	Zeiss Telikon	German telephoto (Ph.302).
40 in.	f/8	Bausch and Lomb Telephoto	Tested against 36-in. Booth (Ph.325).

* Lenses generally produced only as prototypes or in small quantities during World War II, which show the greatest promise for the future.

† The lenses found most useful and produced in large quantities.

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I. *Chapter 12*

Some of the more important characteristics of the optical systems of the OSRD sights are collected in Table 1 on page 582. Although the significance of most of the column heads is quite obvious, several need the explanations given below:

Field: Radius of field in mils. If suitable only for reticle pattern of concentric circles with no radial lines, the letter r is appended.

P_0 Parallactic range at center of field.

P_e Parallactic range at edge of field.

Notes: May include any necessary remarks. In particular the type of lens system for lens sights is indicated. The number of lenses is given by the initial numeral in parenthesis.

Model: For sights of which models have been made, the aperture is given by the initial number. The letter A or B indicates the type of model. Type A is a model designed to serve as a production prototype, built to be mounted and used under service conditions. Type B is a model in which the reticle and collimator are mounted in their correct relative positions for optical testing, with or without illuminator and reflex mirror. A 0 indicates that no model was made.

Optical characteristics of reflex sights.

Designation	f-ratio	Field	P_0	P_e	Notes	Model
Lens sights						
Yerkes L9b	2.0	250r	1.1	3.0	(2) Cemented	3.5-in. B
Yerkes L9k (T-95)	2.0	280r	1.1	3.2	(2) Cemented	2.75-in. A
Mount Wilson Ross-2	2.7	250r	3.1	2.7	(2) Separated	3.75-in. B
Rochester S-1	2.5	70r	1.3	2.0	(2) Separated	3.5-in. B
Rochester S-2	3.0	150	0.6		(2) Separated	3.5-in. A
Rochester Flightsight	3.5	12.5	0.2	0.2	(2) Separated	3.5-in. A
Rochester T-67	3.0	50	1.0		(2) Cemented	40-mm A
Yerkes T-28	2.0	210r	0.7	0.8	(3) Cem. doub. and sing. el.	0
Yerkes T-32	2.0	250r	0.9	1.2	(3) Cem. doub. and sing. el.	3.5-in. B
Mount Wilson Ross-3	1.4	250r	2.4	4.2	(3) Cem. doub. and sing. el.	4.0-in. B
Polaroid	1.9					3.0-in. B
Yerkes P-7	2.4	250	0.5	1.7	(4) 1 Cem. doub. 1 Sep. doub.	0
Yerkes UP-10	2.4	250	0.6	1.0	(4) 2 Sep. doub.	3.5-in. B
Rochester T-94	1.6	280r	0.4	4.5	(4) 2 Cem. doub.	60-mm A
	2.0	210r	0.2	3.9	(4) 2 Cem. doub.	50-mm A
Polaroid	1.6	105	0.3	0.6	(4) 2 Cem. doub.	3.5-in. A
Lens Mangin sights						
Yerkes LSM-4	1.3	210	0.3	0.9		0
Yerkes LSM-7	1.3	210	0.3	0.9	CHM plastic	0
Yerkes LSM-10	1.3	210	0.3	0.9		4x6-in. B
Solid sights						
Mount Wilson Hayward S-1	1.3	160	0.0	3.1	Mangin	1x1-in. A
Yerkes M-16	1.3	210	0.0	0.5	Lens-Mangin	0
Rochester S-2	1.7	125r	1.0		Glass lens plastic prism	3.5-in. A
Double Mangin sight						
Yerkes DM	1.0	75				0
Schmidt sights						
Straight Schmidt	0.7	100	0.0	1.3		0
Mount Wilson Bowen sight	2.0	200	1.0	1.0	Exit pupil 4.5 in.	9x4.5-in. A

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II. *Chapter 12*

Specifications—lens sights.

Component	Radius	Thickness	Material	Aperture
A. Yerkes L9B $F = 4$ in.				
	+2.491			
Lens		0.657	BSC-2	2.00
Cemented	—1.611			
Lens		0.160	LF-3	2.00
	—6.78			
		3.486		
Reticle	—1.263			1.79
B. Yerkes L9k $F = 4$ in.				
	+2.519			
Lens		0.650	BSC-2	2.00
Cemented	—1.564			
		0.157	LF-2	2.00
	—6.27			
		3.529		
Reticle	—1.257			2.00
C. Mount Wilson Ross 2 lens $F = 5.3$ in.				
	+3.402			
Lens		0.304	DBC-1	2.00
	—3.402			
		0.025		
	—3.135			
Lens		0.063	EDF-3	2.00
	—12.6			
		4.862		
Reticle	—1.68			2.38
D. Rochester S-1 $F = 222$ mm				
	+121.3			
Lens		22.0	C-1	89
	—121.3			
Air		3.92		
	—108.2			
Lens		7.02	DF-2	89
	—422.0			
		198.1		
Reticle	—80.2			
E. Rochester S-2 $F = 266.7$ mm				
	+145.5			
Lens		19.7	C-1	89
	—145.5			
Air		4.7		
	—130.6			
Lens		6.0	DF-3	89
	—511.1			
		242.9		
Reticle	—93.6			
F. Rochester Flightsight $F = 305$ mm				
	+166.5			
Lens		30.2	C-1	89
	—166.5			
Air		5.38		
	—148.6			
Lens		9.64	DF-2	89
	—579.4			
		283.3		
Reticle	∞			
G. Rochester T-67 $F = 119.8$ mm				
	+72.58			
Lens		9.0	BSC-1	40
Cemented	—57.08			
Lens		4.0	EDF-2	40
	—152.13			
		113.5		
Reticle				
H. Yerkes T-28 $F = 4$ in.				
	+5.61			
Lens		0.253	BSC-2	2.00
	—7.78			
Air		0.006		
	+1.835			
Lens		0.479	BSC-2	2.00
Cemented	—5.75			
Lens		0.143	EDF-1	2.00
	+3.281			
		3.175		
Reticle	—0.994			1.48
I. Yerkes T-32 $F = 4$ in.				
	+5.39			
Lens		0.242	BSC-2	2.00
	—7.69			
Air		0.006		
	+1.772			
Lens		0.467	BSC-2	2.00
Cemented	—5.72			
Lens		0.137	EDF-1	2.00
	+3.17			
		3.071		
Reticle	—0.99			1.70
J. Mount Wilson Ross 3 lens $F = 2.8$ in.				
	+3.813			
Lens		0.376	DBC-1	2.00
Cemented	—2.073			
Lens		0.093	EDF-3	2.00
	—32.6			
Air		0.111		
	+1.925			
Lens		0.278	DBC-1	2.00
	+7.77			
		2.369		
Reticle	—0.907			1.48
K. Polaroid $f/1.9$ $F = 145$ mm				
	+87.69			
Lens		21.0	CHM	76.20
Cemented	—83.90			
Lens		5.07	Styrene	76.20
	+439.4			
Air		0.43		
	+83.20			
Lens		10.28	CHM	76.20
	+203.9			
		120.0		
Reticle	. . .			

[redacted]

Component	Radius	Thickness	Material	Aperture
L. Yerkes P-7 $F = 4.8$ in.				
	+2.661			
Lens		0.444	BSC-2	2.00
Cemented	−2.661			
Lens		0.194	DBF-1	2.00
	∞			
Air		1.332		
	+2.758			
Lens		0.194	DBF-1	2.00
	+1.828			
Air		0.259		
	+2.852			
Lens		0.254	BSC-2	2.00
	−41.1			
		2.828		
Reticle	−7.03			2.40
M. Yerkes UP-10 $F = 4.8$ in.				
	+2.908			
Lens		0.421	BSC-2	2.00
	−2.736			
Air		0.028		
	−2.581			
Lens		0.139	DF-2	2.00
	−19.85			
Air		1.382		
	+4.000			
Lens		0.167	DF-2	2.00
	+2.286			
Air		0.137		
	+5.08			
Lens		0.249	BSC-2	2.00
	−5.08			
		2.886		
Reticle	−5.76			2.40
N. Rochester T-94 $F = 102.33$ mm				
	+82.8			
Lens		14.0	BSC-1	60 or 50
Cemented	−90.3			
Lens		2.0	DF-3	60 or 50
	∞			
Air		0.0		
	+82.8			
Lens		14.0	BSC-1	60 or 50
Cemented	−90.3			
Lens		2.0	DF-3	60 or 50
	∞			
		84.3		
Reticle	−32.0			
O. Polaroid $f/1.6$ $F = 142$ mm				
	+272.38			
Lens		23.89	CHM	88.9
Cemented	−111.82			
Lens		7.28	Styrene	88.9
	−261.17			
Air		0.00		
	+72.79			
Lens		30.07	CHM	88.9
Cemented	−165.68			
Lens		10.26	Styrene	88.9
	+160.32			
		100.06		
Reticle	...			

P. Yerkes LSM-4 No data available.

Q. Yerkes LSM-7 $F = 3.9$ in. Aperture 2.67x3.33 in.

Radii	*Separations*
1. 4.60	
	AB 0.15
2. 11.2	
	BC 1.10 CD 1.59
3. 3.77	
	DE 0.12
4. 6.20	
	CF 1.62

Reticle 3.23 Diameter 1.73
Material CHM for all elements except inner mirror
Mirror plate glass 0.04 thick.

R. Yerkes LSM-10 $F = 3.9$ in. Aperture 2x3 in.

Radii	*Separations*
1. 4.44	
	AB 0.19
2. 9.98	
	BC 1.35 CD 1.38
3. 3.70	
	DE 0.25
4. 6.11	
	CF 1.64

Reticle 3.33 Diameter 1.2
Inner mirror glass 0.12 thick
Material BSC-2 glass

S. Mount Wilson Hayward sight S-1 $F = 1.89$ in. in glass Aperture 1x1

Radii	*Separations*
Reticle 1.305	
	AB 1.2565
1. 5.7	
	BC 0.6
2. 3.2	
	CD 0.022

Reticle diameter 0.52
Material BSC-1

T. Yerkes M-16 $F = 4$ in. in glass. Aperture 2x2

Radii	*Separations and Material*	
Reticle 3.26		
1. 17.4	AB 2.40	BC 1.00 CHM
2. 7.76	CD 0.004	air
3. 18.4	DE 0.172	Styrene
4. 5.69	EF 0.291	air

Reticle diameter 1.12

U. Rochester S-3 $F = 135.3$ mm

Component	*Radius*	*Thickness*	*Material*	*Aperture*
	+166.7			
Lens		7.0	C-1	89
	∞			
Air		0.0		
	+114.6			
Plastic Prism		198	Plastic $n_D = 1.495$	89
Reticle				

V. Double Mangin sight no data.

W. Straight Schmidt sight no data.

X. Mount Wilson Bowen sight $F = 4.474$ in.

	Radius	*Separation*
Primary mirror	9.0	
		4.526
Reticle	4.474	

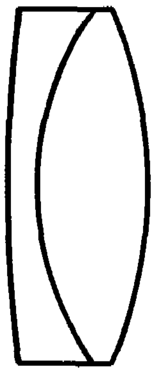
Y. Eastman Kodak Fly's-Eye sight See OSRD Report No. 6281.

[redacted]

III. *Chapter 12*

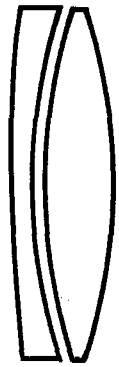
The following diagrams are included to show the general forms of all the collimators listed in Appendix II of Chapter 12. No attempt at great accuracy in drawing has been made, and several instances will be found where one drawing represents several related collimators.

TWO LENS TYPES

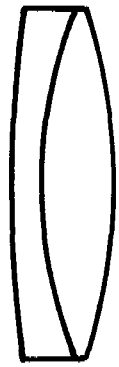


YERKES
A L9b
B L9k (T-95)

MOUNT WILSON ROSS
C 2 LENS

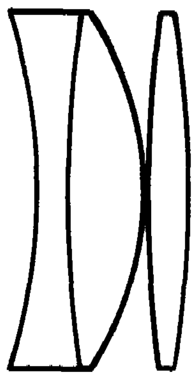


ROCHESTER
D S-1
E S-2
F FLIGHT SIGHT

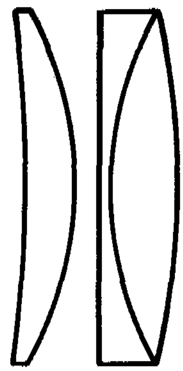


ROCHESTER
G T-67

THREE LENS TYPES

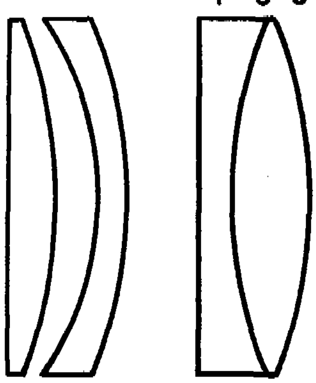


YERKES
H T-28
I T-32

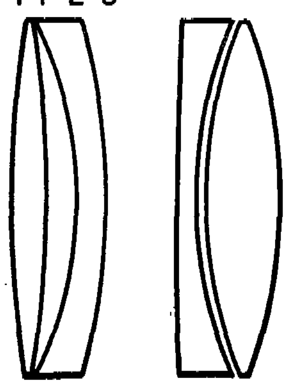


MOUNT WILSON ROSS
J 3 LENS
K POLAROID f/1.9

FOUR LENS TYPES

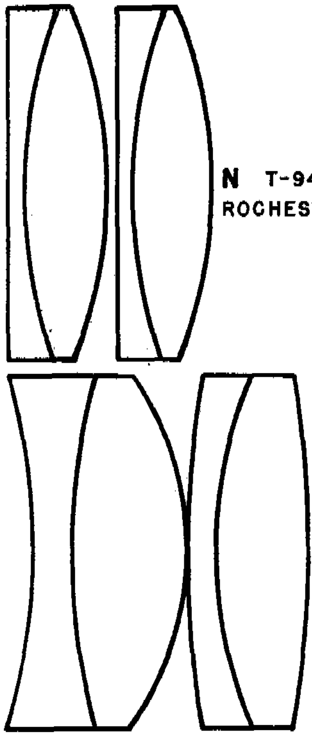


YERKES
L P-7



YERKES
M UP-10

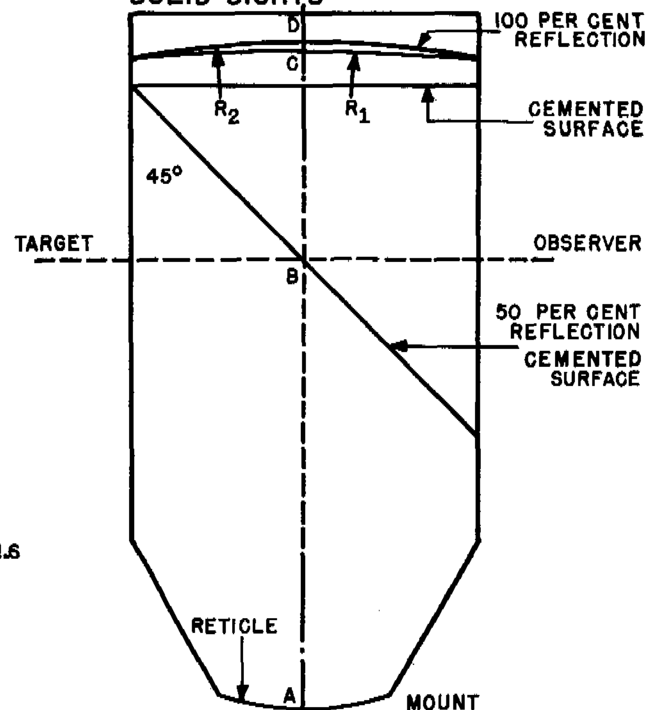
FOUR LENS TYPES



N T-94 ROCHESTER

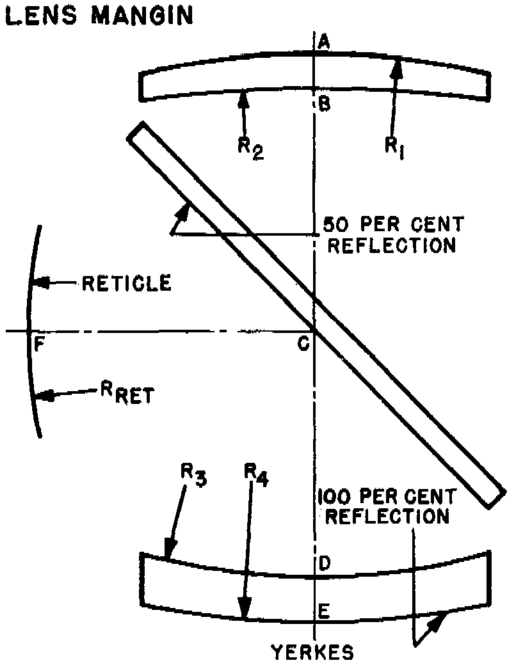
O POLAROID f/1.6

SOLID SIGHTS

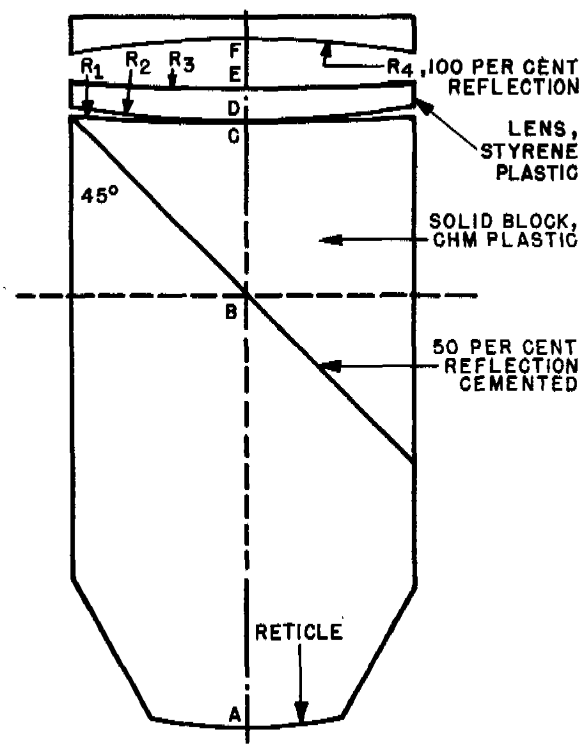


S HAYWARD S-1 MOUNT WILSON

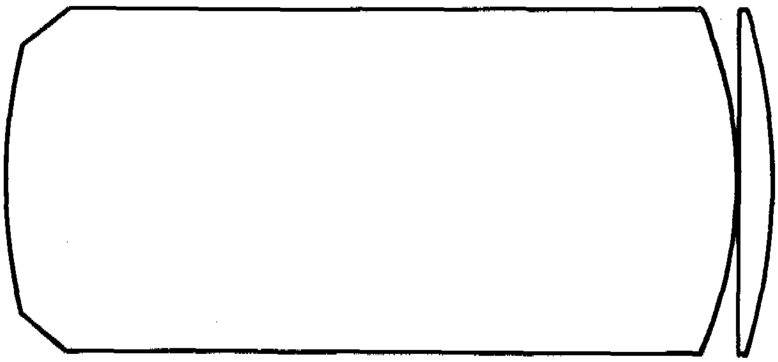
LENS MANGIN



P LSM 4
Q LSM 7
R LSM 10

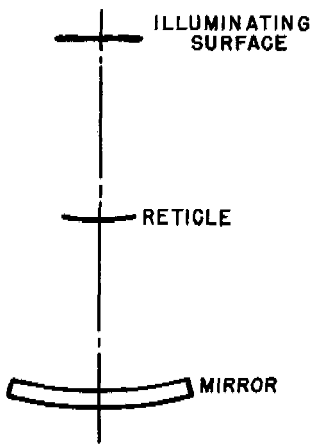


T M-16 YERKES



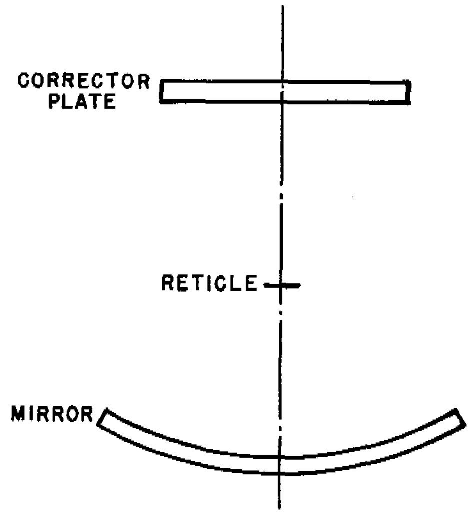
ROCHESTER

U S-3
SOLID SIGHT



MOUNT WILSON

Y BOWEN SIGHT



X STRAIGHT SCHMIDT

[redacted]

GLOSSARY

Aberration. In optics the failure of rays of light to converge to a point focus, measured by the departure in angular measure, or in linear measure in the focal plane, of the ray in question from the ideal point.

Achromatic. Corrected, as well as possible, for color.

AI Equipment. Airborne radar used in interceptor planes.

Alicyclic Rings. A name applied to compounds containing a ring of carbon atoms but not belonging to the aromatic series.

Altazimuth. A design for a mounting which employs two axes of rotation—one horizontal and the other vertical.

Anastigmat. An optical system that is corrected over a wide angular field for astigmatism, and usually for curvature of field. The term is loosely used and has been applied to lenses of widely varying quality.

Anti-Vibration. Capable of removing external vibrations from an isolated member.

Anion. The product evolved at the anode in electrolysis. In general a negative ion.

AOM. Anti-Oscillation mount.

Aperture. The area of a lens through which the light may pass, or a diaphragm which limits the size of of a light beam in an optical instrument.

Apochromatic. A type of color correction that combines three or more colors into a common focus, as contrasted with the usual achromatic correction for which two colors are combined. In its strictest sense, an apochromatic optical system is one corrected for secondary spectrum for three colors, and for spherical aberration and coma for two. The designation is often loosely used.

Armorer. A technician trained in the adjustment of guns, turrets, and associated equipment.

Aspheric Surface. An optical surface that departs from a spherical form. Optical instruments having rotational symmetry usually employ spherical surfaces for production simplicity.

Astigmatism. An off-axis aberration. Radial and tangential lines are in focus in different planes.

Atomic Refractivity. The product of the specific refraction of an element by its atomic weight.

Auxiliary Magnification. The magnification of an auxiliary telescope employed as an aid to the eye in the inspection of optical instruments.

AVM. Anti-vibration mount. Often synonymous with anti-oscillation mount, although the latter usually pertains to angular vibration only.

Baffle. A plate or wall to deflect, check or otherwise regulate flow.

Ball-Cone Mount. A type of AOM developed at the Kodak Research Laboratories.

Birefringence. The property of double refraction, which is said to be high or low according as the difference between refractive indices is large or small.

Bloom. A surface coating or appearance; a milky appearance on the surface of glass.

Blue Cane Glass. Calcium-sodium silicate glass in the form of rods, or "canes."

Bore-Sighting. Alignment of camera optical axis with that of the bore of the gun.

Carboxyl Group. The group of most organic acids, such as formic, acetic, and benzoic, which have the univalent radical CO_2H in common.

Center-of-Gravity Mount. Arrangement of mounting elements with respect to the center of gravity of the isolated member such that linear motions cannot produce rotational motions and vice versa.

Centipoise. A measure of viscosity. It is one hundredth of a poise.

Chromatism. Chromatic aberration, the result of varying focus of a lens for different wavelengths of light.

Chunk Glass. Large irregular fragments of glass produced by fracturing of the solidified glass mass in the melting pot.

Circle of Confusion. The disk, of measurable diameter, by which a point in the object is represented in the image formed by a lens.

Cobb Chart. A type of testing target involving pairs of bright lines on a dark background, grouped in descending size according to a fixed ratio.

Collective. A lens near a focal plane whose purpose is to increase the light transmission of a telescope.

Collimator. A lens or mirror system which renders the rays of light from a point parallel.

Collinear. Lying on a straight line.

Coma. An off-axis aberration in the focus due to the different zones of an optical system having different magnifications.

Contour (cartography). A line on a map passing through points all at the same elevation, to show heights.

Contour Follower. A cam which limits the vertical motion of a gun at certain bearings, to avoid hitting parts of the aircraft which would otherwise be exposed to fire.

Contrast. The ratio of surface brightness of respective objects. Measured by direct ratio, or by log of this ratio, or by density difference, or by slope of the straight line portion of the characteristic curve. Also occasionally measured in units of an adopted basic contrast.

Control (cartography). Dimensional or angular information used in mapping, to determine the scale of the map, the positions of points, etc. Usually consists of the coordinates or elevations of certain points, the distance between two points, or the direction of a line.

Coplanar. Lying in a plane.

Correcting Plate. A lens-like glass plate with slightly deformed surface that is used in an optical system to alter the course of the rays by differential amounts.

Crabbing. Side motion or drift of aircraft relative to the ground, usually caused by wind.

Curvature of Field. A lens defect such that image points of a plane source do not lie in a plane.

Damper. Element of anti-vibration mount whose function is to reduce the natural frequency amplitude and to prevent oscillation.

Definition. A property of an optical system which relates to the system's ability to produce sharp, distinct images.

Deflection. The angle by which a gun must be aimed ahead of a moving target in order to hit it.

Deflection Shooting. Shooting at a moving target which requires appreciable deflection in aiming.

Dendritic. Pertaining to dendrite or to arborescent crystallization.

Dial Gauge. A device which indicates on a dial very small variations in a fixed dimension.

Diopter. A unit used to express the power of a lens. It is equal to the reciprocal of the focal length in meters.

Dioptometer. A device which permits the measurement of the degree of convergence or divergence of light rays.

Dispersive Power. The property of a medium to separate light of different wavelengths, as in a spectrum.

Distortion. A lens defect such that the image produced by the lens does not have the same shape as the object.

Dodging. The controlled alteration of density between negative and print for the purpose of equalizing print quality, usually accomplished by shadowing the printing light.

Doublet. An optical combination of two lenses, usually an achromatic pair.

Dynamic Boresighting. Boresighting in the presence of vibration.

EK. Eastman Kodak Company.

Entrance Pupil. The effective area through which image forming rays may enter an optical system.

Erecting Prism. A prism that rotates the field of view through 360 degrees to compensate for inversion of the objective.

Erector. A lens combination which inverts the image in a telescope so that the observer sees the field right side up.

Exit Pupil. The area through which rays may leave an optical instrument and enter the eye.

Exposure. In photography, the total effect of the product of time and intensity.

Eye Freedom. The transverse distance through which the observer's eye can be moved and still see all of the reticle pattern at the normal eye position.

Eyepiece. The lens or lenses by which the image formed by the objective may be examined by the observer.

Eye Relief. The distance from eye lens to effective exit pupil of the system.

Eye Space. The space from which all of the reticle pattern can be seen.

f-Number. The ratio of aperture to focal length, much used in photography as a measure of lens speed.

Field. The angular extent of the portion of the object space which may be seen through a telescope by moving the eye only.

Field-Flattener. A lens or deformed plate placed near the focal plane for the purpose of depressing an otherwise curved focal surface into a plane surface.

Filtering Action. Mechanical filtering action analogous to electrical filtering to attenuate all frequencies above a certain lower limit.

Flat. A piece of optical glass one of whose surfaces has been ground and polished to a flat surface.

Flexible Gun. A gun whose direction of aiming relative to the aircraft can be changed.

Fly's-Eye Sight. A reflex sight of large exit pupil made up of a surface of many small lenses (and thus resembling a fly's eye), each of which has its own reticle. To the observer the effect is the same as though there were only one large lens in use.

Focal Length. The distance from the principal plane to the focus of a lens.

Focal Plane. A plane perpendicular to the optical axis passing through the focal point on the axis.

Focal Surface. The surface of best focus over a field, generally curved.

Fork Lift. A small truck, ordinarily used for stowing boxes, provided with a horizontal fork which can be used to lift objects, usually about 9 to 12 ft above the ground.

Foucault Test Chart. A group of equally spaced parallel black lines. The spacing between the lines is equal to the width of the lines.

Frictional Damping. Damping in which the resisting force is essentially independent of velocity. Also called Coulomb and dry friction damping.

Fringes. Dark bands in the field of an interferometer.

Gimbal Mount. A type of AOM developed at the Institute of Optics, University of Rochester.

Ground Speed. Velocity of aircraft relative to the ground.

Gunner. The operator of a sight which controls a gun.

Gunsight. As used in connection with flexible gun installation, refers to the gyro-controlled lead computing sight. A collimated reticle image is seen superimposed on the target by means of a reflecting glass plate.

Halides. Binary compounds (chlorides, bromides, iodides, or fluorides) of halogens with an element or radical.

Hardstands. Hard surfaced areas for the parking of aircraft.

Harmonization. The adjustment of the direction of aim of a gun and sight parallel to one another, sometimes taking account of ballistic corrections.

Harmonization (Mirror Boresight Method). A method based on the use of a mirror, mounted accurately at right angles to a mandrel which fits a

collet in the gun barrel, to set parallel to one another the sight and the gun which it controls.

HARMONIZATION (MIRROR FRAME METHOD). A method based on the use of a group of flat mirrors mounted parallel to one another on a frame, for setting a group of guns and sights parallel.

HARMONIZATION (PRISM METHOD). A method based on the use of two double-image prisms to establish two parallel lines of sight.

HARMONIZATION (WIRE METHOD). A method based on the use of a wire under tension and level bubbles to establish two parallel lines of sight.

HAZE. In aerial photography the scattering back toward the camera lens of sunlight from air, moisture, and dust below the plane.

HYDROLYSIS. A chemical decomposition involving addition of the elements of water.

HYDROPHILIC. Having, or denoting, strong affinity for water.

HYPERCHROMAT. An optical combination with enhanced color characteristics, often used for eliminating excess color in some other part of the system.

INCLUSIONS. Regions of non-homogeneous material in optical glass.

INDEX-ν CURVE. A relation between the ν-value and the index of refraction for inorganic glasses; in general the higher the ν-value, the lower the refractive index.

INTERFEROMETER. A device which compares optically the lengths of two light paths.

INTERVALOMETER. Device for automatically making the power electrical connection to trip the camera shutter at a preset time interval.

INVARIANT SYSTEM. An optical system in which a motion or rotation of the system as a whole causes no apparent motion of the image.

INVERTED TELEPHOTO. An optical system that is much longer than the equivalent focal length, usually obtained by the negative power preceding the positive.

JACKS. Adjustable supports used to steady the wings and tail of aircraft on the ground.

KINETIC DEFINITION CHART APPARATUS. A device, used as a target, designed to measure the definition or resolving power of an optical instrument.

KRL. Kodak Research Laboratories.

LATERAL COLOR. An off-axis aberration due to different magnification in the different colors.

LEAD. Deflection.

LEAD COMPUTER. A device for computing the lead. Frequently connected mechanically to a sight to automatically deflect it by the proper angle.

LIPOPHILIC. Having, or denoting, a lack of affinity for water.

LONGITUDINAL CHROMATISM. The axial difference in focus of a lens for rays of different color.

LOUVRE SHUTTER. A Venetian-blind type shutter.

MACROSCOPIC. Pertaining to objects of large size, relative to the scale of values under consideration; the opposite of microscopic.

MAGNIFICATION FACTOR. Same as transmissibility.

MANGIN MIRROR. A spherical mirror formed by aluminizing or silvering the back surface of a lens so designed that the front surface corrects the spherical aberration of the mirror.

MAR RESISTANCE. The ability of a surface to withstand scratching by particles of carborundum falling from a given height.

MICROMETER. A device for the accurate measurement of short distances.

MICROSCOPIC. Pertaining to objects of small size, relative to the scale of values under consideration; opposite of macroscopic.

MICROPHOTOMETRY. The study of photometric problems on a microscopic scale, generally involving the photographic emulsion.

MIL. An angle equal to 0.001 radian.

MINUS-BLUE FILTER. In aerial photography, a filter that eliminates blue and violet light. Generally the equivalent of Wratten No. 12.

MIRROR BORESIGHT METHOD. *See* HARMONIZATION.

MIRROR FRAME METHOD. *See* HARMONIZATION.

MONOCHROMATOR. A device for isolating a single wavelength of light at a time; in practice, a narrow band of wavelengths.

MOSAIC. A composite picture made by piecing together prints of a number of negatives of contiguous areas, all of the same scale.

MOSAIC (CONTROLLED). A mosaic in which the method of processing and assembling the photographs assures that the images are in correct horizontal relationship one to another, to within some tolerance.

MOSAIC (PHOTOGRAPHIC). Portions of many aerial photographs assembled in such a fashion that images match at the joints, thus giving a photographic representation of a large area.

MOSAIC (UNCONTROLLED). A mosaic in which the photographs are assembled by matching images only.

n_D. The index of refraction at the sodium D line λ5893 A.

NATURAL FREQUENCY. The undamped resonant frequency.

ν-VALUE. The ratio $(n_D - 1)/(n_F - n_c)$ where n_D, n_F, n_c are the indices of refraction at wavelengths 5893, 4861, 6563 A respectively. It is a measure of the dispersive power of a glass.

OBJECTIVE. The principal image forming lens of a telescope.

OBLIQUE AERIAL PHOTOGRAPH. An aerial photograph taken with the camera axis significantly off the vertical.

OBLIQUE AERIAL PHOTOGRAPH (HIGH). One in which the horizon appears.

OCULAR. An eyepiece.

OFF-AXIS ABERRATION. Aberration for points in the field away from the optical axis.

OPHTHALMIC. Pertaining to optics of the eye; ophthalmic glass is glass produced for spectacle lenses.

OPTIC. The glass components of any optical device or the combination of the components.

OPTICAL AXIS. An imaginary line passing through the

centers of curvature of the various lens surfaces.

ORANGE-PEEL SURFACE. The descriptively named surface which results from the sudden, uneven chilling of the surface of a hot piece of glass in the plastic state as it comes in contact with the relatively cool surface of a metal mold.

PANATOMIC X. A special emulsion of high speed and fine grain. Class A.

PARALLACTIC RANGE. The extreme parallactic shift as the eye traverses a diameter of the aperture of a sight, expressed in mils.

PARALLAX. The apparent shift of the reticle image with respect to a distant object as the eye traverses the aperture of a sight.

PARTIAL DISPERSION. The difference in the index of refraction at two designated wavelengths.

PETZVAL SUM. A condition in optics involving the sum of simple functions of the radii and indices of an optical system, intimately related to curvature of field in the absence of astigmatism.

PHOTOMETRIC AREA. An area of uniform and known brightness, used for standardizing the general exposure level, and sensitivity of the emulsion.

PHOTOMICROGRAPHY. Microscopy by photographic methods.

PLATEN. A reference plate or surface, used for locating the film.

PLASTICISE. To render plastic; to break down.

POLAR GROUP. A union of atoms in which the chemical bond is electrostatic attraction between oppositely charged particles (ions).

POLYHYDROXY. Containing more than one hydroxyl group, the latter being a univalent group or radical consisting of one atom of hydrogen and one of oxygen.

PORRO PRISM. An erecting prism frequently used in binocular systems made of two right-angle prisms. There are four internal reflections from the sides of the prisms. The hypotenuse faces in part are the entrance and exit faces of the prism. The other parts of the hypotenuse faces are usually in cemented contact.

PRISM. An optical device for changing the direction of a beam of light.

POLAR AXIS. An axis, parallel to that of the earth, on which an instrument rotates.

PRISM METHOD. *See* HARMONIZATION.

PROBABLE ERROR. An increment and decrement to be applied to the observed value of a quantity such that for a large number of observations half the values will lie within the interval so obtained and half without.

PROBE. A slender rod, used to measure the growth of a crystalline mass.

PROBOSCOPE. A device by which the interior surfaces of the lenses in an optical instrument may be examined.

RANGEFINDER. A device for measuring the range of a target, whose dimensions may be unknown, by measuring the difference in its apparent direction as seen from the two ends of a fixed base line within the instrument.

RAYLEIGH LIMIT. A principle enunciated by Lord Rayleigh, that phase differences of the order of ¼-wavelength of light will not detract noticeably from the limiting resolution of a converging pencil of light.

RAY TRACING. A method of computing the performance of a lens system by tracing a ray from lens surface to lens surface through the instrument.

REFRACTIVE INDEX. The ratio of the velocity of light in a vacuum (or in air) to that in any other medium.

RESOLUTION. Generally, the fineness of detail resolvable. Often used as the equivalence of resolving power, which is properly its reciprocal.

RESOLVING POWER. The ability of an instrument to show a group of parallel lines as separated, generally expressed in terms of the minimum angle of separation of the lines still shown as separated.

RESOLVING-POWER TARGETS. A group of targets designed for quantitative study of the various factors that limit resolution.

RETICLE. An optical device which superimposes a group of lines and divisions upon the field of a telescope.

RUBBER SHELL MOUNT. A type of AOM developed at the Technicolor Motion Picture Corporation.

SCANNER. A scanning device.

SCANNING DEVICE. A device which, by optical and mechanical means, presents to an observer who looks into fixed eyepieces, a series of continuously or intermittently changing fields which cover systematically a sector of the horizon or of the sky.

SCAVENGER. A material introduced into a chemical process to carry off impurities in a reaction.

SCOTOPTIC VISION. Vision at low levels of illumination.

SECONDARY SPECTRUM. The residual color aberration remaining in an optical system after it has been achromatized for two wavelengths.

SEEDS. Very small inclusions.

SHAKE TABLE. An instrument for testing the effects of linear and angular vibration upon AOM systems.

SHOCK MOUNTING. A resilient mounting used to protect such apparatus as flight instruments and radio equipment from damage by plane vibration and mechanical shock.

SLAB GLASS. Glass manufactured in long continuous sheets.

SLEEK. A glossy scuff on the surface of an optical element.

SPHERICAL ABERRATION. An optical error of a lens which results from a difference in focal length between the central and marginal areas of the lens.

STACKER. *See* FORK LIFT.

STADIAMETER. A device for determining the range of a target whose linear dimensions are known by measuring the angle which it subtends at the observer.

STATIC BORESIGHTING. Boresighting in the absence of vibration.

STONES. Inclusions somewhat larger than seeds.

STRAIN. A defect in optical glass produced by non-uniform contraction during the cooling of the glass.

STRIAE. A defect in optical glass produced by regions of slightly varying index of refraction.

SUPER XX. A special emulsion of very high speed and medium graininess; for aerial purposes, with enhanced red sensitivity. Class L.

SWEEP. Method of motion compensation by swinging the entire camera about a transverse axis.

TELEPHOTO. An optical system whose equivalent focal length exceeds its overall physical length to the focal plane. In ordinary photography, used loosely for any lens of long focal length, particularly in miniature photography.

TMP. Technicolor Motion Picture Corporation.

T. O. The Army Technical Order describing a procedure.

TRANSMISSIBILITY. The ratio of the amplitude of a mounted system to the amplitude of the disturbing vibration.

TURBIDITY. The turbid character of the photographic emulsion that causes diffusion of light and spreading of the image on a microscopic scale.

UR. University of Rochester.

VERTICAL AERIAL PHOTOGRAPH. An aerial photograph taken with the camera axis approximately vertical, usually within 5 degrees.

vpm. Vibrations per minute.

WEDGE. A thin prism which produces small deviations in a light beam.

WIRE METHOD. *See* HARMONIZATION.

ZONAL ABERRATION. The residual spherical aberration left over after optimum balancing of undercorrected third order spherical and overcorrected fifth and higher orders has been accomplished.

Z-NUMBER. Hardness number on the Rockwell scale.

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CONTRACT NUMBERS, CONTRACTORS, AND SUBJECT OF CONTRACTS

Contract No.	*Contractor*	*Subject*
OEMsr-1039	Aero Service Corporation	Aerial mapping methods.
OEMsr-579	Bausch & Lomb	Binoculars.
OEMsr-1229	Brown University	Binocular testing.
OEMsr-389	California Institute of Technology	Reticles.
OEMsr-657	California Institute of Technology	Hardening plastics.
OEMsr-1058	Dartmouth College	Binocular testing.
OEMsr-421	Eastman Kodak Company	Molded glass.
OEMsr-622	Eastman Kodak Company	Shutter development and periscope camera.
OEMsr-1090	Eastman Kodak Company	Night glasses.
OEMsr-392	Eastman Kodak Company	Aerial cameras.
OEMsr-503	Eastman Kodak Company	Theodolites.
OEMsr-707	Eastman Kodak Company	Anti-glare shutter.
OEMsr-1087	M. Flood and Associates	Mapping methods.
OEMsr-474	Harvard College	Optical design.
OEMsr-203	Massachusetts Institute of Technology	Testing.
OEMsr-45	Massachusetts Institute of Technology	Optical crystals.
OEMsr-101	Mount Wilson Observatory	General optical problems.
OEMsr-1197	Pennsylvania State College	Inspection methods.
OEMsr-1177	Perkin-Elmer Corporation	Crystal lenses.
OEMsr-70	Polaroid Corporation	Optical plastics.
OEMsr-100	Stanford University	Glare protector.
OEMsr-710	Technicolor Motion Picture Corporation	Langer shutter.
OEMsr-617	Technicolor Motion Picture Corporation	Scanning devices.
OEMsr-1078	University of Chicago (Yerkes)	Design of optical instruments.
OEMsr-1115	University of Michigan	Stabilizing devices.
OEMsr-1245	University of Michigan	Exposure meter.
OEMsr-205	University of Pennsylvania	Tropical deterioration.
OEMsr-1228	University of Pennsylvania	Binocular performance.
OEMsr-871	University of Pittsburgh	Clouding of optical glass.
OEMsr-160	University of Rochester	Night vision.

SERVICE PROJECT NUMBERS

The projects listed below were transmitted to the Executive Secretary, NDRC, from the War or Navy Department through either the War Department Liaison Officer for NDRC or the Office of Research and Inventions (formerly the Coordinator of Research and Development), Navy Department.

Service Project Number	*Subject*
AC-11	Optical glass substitutes.
AC-26	Night glasses and night sights.
AC-29	Photographic equipment research.
AC-88	Testing of aerial photographic equipment.
AC-99	Shock-proof gun camera mounts.
AC-113	Quick developing camera (assigned to Section 16.5).
AC-114	Location of tactical targets by air search.
AC-127	Aircraft armament harmonization studies.
AC-131	Development of an optical viewfinder for use in aerial photography.
CE-8	Enlarging field of view of night glasses without sacrifice of power and without increase in weight.
CE-9	Quantity producing of optical glass.
CE-21	Telescope for one-second theodolite.
CE-27	Elimination of reflection from glass surfaces.
NA-124	Development of photogrammetric instruments and techniques.
NA-140	ASW project combining searchlight and night glasses.
NA-176	Development of photographic lens shutter.
NA-200	Wide angle projection system (dome trainer).
NO-97	Application of nonreflecting films to the surfaces of optical instruments.
NO-98	New methods of reticle manufacture.
NO-103	Night interceptor sight.
NO-127	Pressure proof binoculars.
NO-210	Night binocular design study. Extension: Visibility data of infrared sources.
NR-111	Design and construction of periscopic aircraft sight.
NS-105	Anti-vibration mounted double system binoculars. Amendment: Development of anti-vibration mounting for shipborne binoculars for lookout purposes.
NS-236	Development of new eyepiece design for 7x50 binoculars.
NS-242	Periscope camera with quick-developing film.
OD-43	Investigation of film formation on optical surfaces.
OD-48	Phototheodolites for aerial position finding. Extension: Development of precision timing equipment for fire control data recorders.
OD-116	Anti-oscillation mount for binoculars in tanks.
OD-119	Optical fire control equipment (telescopes T-44 and T-76).
OD-128	Development and manufacture of pilot models of telescope T-108.

Service Project Number	*Subject*
OD-129	Development and construction of pilot models of binoculars of the periscopic type.
OD-138	Development of improved methods of testing and inspecting optical instruments. Extension: Study of the effects of striae on the performance of optical instruments.
OD-146	Study of sighting devices for computing sight M7 and M45.
OD-149	Design of telescopes T-118 and T-119.
OD-180	Telescope T-136.
16.1-1	Studies of stabilizing devices.
16.1-2	Testing of optical systems.
16.1-3	Stadiameters.
16.1-4	Scanning devices.
16.1-5	Reflex sights.
16.1-6	Vision studies.
16.1-7	Submarine periscope design and photographic performance.
16.1-8	Anti-glare shutter.
16.1-9	Panofsky stabilizer.
16.1-10	Foxhole periscope.
16.1-11	Panofsky stabilizer.

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